THE JOURNAL OF THE AMERICAN CERAMIC SOCIETY, MAY 1, 1945

THE JOURNAL

OF THE

AMERICAN CERAMIC SOCIETY

JUNE 1, 1945

MONTHLY PUBLICATION DEVOTED TO THE ARTS AND SCIENCES RELATED TO THE SILICATE INDUSTRIES

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Publication Office: 20th & Northampton Sts., Easton, Pa.
Editorial Office: 2525 N. High St., Columbus 2, Ohio
Committee on Publications: R. L. Stone, *Chairman;* Harry Thiemecke, W. A. Weldon, K. C. Lyon, and R. C. Purdy, *ex officio*

Entered as second-class matter at the post office at Easton, Pa., under the act of March 3, 1879. Published monthly.
Subscription fifteen dollars ($15.00) a year. Single numbers $1.50
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THE JOURNAL
OF
THE AMERICAN CERAMIC SOCIETY

Volume 28 June 1, 1945 Number 6

MICROSTRENGTH OF GLASS*

By H. E. Powell and F. W. Preston

Abstract

It is shown experimentally that if a minute area of a large piece of glass is tested for tensile strength, the stress supported is comparable with that of fine glass fibers and is some fifty or one hundred times the "strength" of the large piece tested in any of the ordinary ways. The experiment consists in pressing a small steel ball upon the glass surface, and so stressing, in tension, a minute annular zone around the circle of contact.

I. Introduction

It is well known that small specimens of glass can usually stand a higher stress than large samples; for instance, fibers are usually stronger than rods, and the strength increases as the fiber diameter decreases.[1] Similarly, it has long been recognized that a fine metal wire will usually carry a higher unit stress than a heavy wire or rod.

In the testing of glass laths or rods by cross bending, it has been recognized that the area subject to high stress is of more importance than the size of the specimen, and ingenious and in some cases intricate theories have been developed to account for this and comparable phenomena.[2]

In the case of fine metal wires, it has been thought that the reorientation of the crystal grains and the effects of "cold-work," while the wire is being drawn, may have much to do with the increased strength[3]; in the case of glass and fused-silica fibers, some glass technologists have thought that orientation of long-chain molecules might have something to do with it,[4] though X-rays fail to show such orientation.[5]

As ordinarily tested, in the form of bottles, plates, laths, or rods, glass is apt to show a tensile strength of from 3000 to 10,000 lb. per sq. in. The strength varies greatly with the duration of the test,[6] with the humidity or wetness of the glass surface,[6] with the

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* Forty-Seventh Annual Program, The American Ceramic Society, Glass Division, No. 14. Received April 11, 1945.

This investigation was a necessary preliminary to a research on the impact strength of glass and glassware. The present report, however, does not deal with impact as such, but with fractures produced under static conditions. The broader research (on impact), as far as the Preston Laboratories are concerned, has had so many ramifications and so many industrial applications that it has never, up to date, been possible to give a coherent account of it. Various phases have at times been sponsored by the Owens-Illinois Glass Company and by the Glass Container Association; sometimes the problems of other firms have cut across the setup; at other times the whole industry, and other industries, have been involved in the applications. The Blue Book of Impact Testing, which was distributed widely some years ago by the Glass Container Association, covered some of the theoretical problems. The Red Book, which was to have covered the experimental evidence, has been greatly delayed by the pressure of war work, the switching of personnel to problems of airplane structures, and the loss of personnel to the armed forces.

The present paper may be regarded, however, as a first installment of the Red Book, and the authors hope, unless the man-power situation gets worse, to follow it up with other excerpts. There is no immediate hope of producing a comprehensive treatise on the whole subject.

[1] (*a*) A. A. Griffith, "Phenomena of Rupture and Flow in Solids," *Trans. Roy. Soc.* [London], **A221**, 163–98 (1920); *Ceram. Abs.* in *Jour. Amer. Ceram. Soc.*, **4** [6] 513–14 (1921).

(*b*) F. O. Anderegg, "Strength of Glass Fiber," *Ind. Eng. Chem.*, **31** [3] 290–98 (1939); *Ceram. Abs.*, **18** [9] 241 (1939).

[2] (*a*) E. Orowan, "Die erhöhte Festigkeit dünner Fäden, der Joffé-Effekt und verwandte Erscheinungen vom Standpunkt der Griffithschen Bruchtheorie," *Z. Physik.*, **86**, 195–213 (1933).

(*b*) James Bailey, "Attempt to Correlate Some Tensile Strength Measurements on Glass," *Glass Ind.*, **20** [1] 21–25; [2] 59–65; [3] 95–99; [4] 143–47 (1939); *Ceram. Abs.*, **19** [4] 89 (1940).

[3] L. Bragg, "Metals," *Endeavour* [London], **2** [6] 43–51 (April, 1943); *Ceram. Abs.*, **22** [11] 203 (1943).

[4] A. Q. Tool, "Molecular Strains and Extraordinary Thermal Effects in Glasses." Presented at the Forty-Fifth Annual Meeting, The American Ceramic Society, Pittsburgh, April 20, 1943 (Glass Division); not published.

[5] (*a*) N. W. Taylor, "Law of Annealing of Glass, Quantitative Treatment and Molecular Interpretation," *Jour. Amer. Ceram. Soc.*, **21** [3] 85–89 (1938).

(*b*) B. E. Warren, "Basic Principles Involved in Glassy State," *Jour. Applied Physics*, **13** [10] 602–10 (1942); *Ceram. Abs.*, **22** [2] 29 (1943).

[6] F. W. Preston, "Mechanical Properties of Glass," *Jour. Applied Physics*, **13** [10] 623–34 (1942); *Ceram. Abs.*, **22** [2] 31 (1943).

degree of abrasion upon the surface,[7] and with the temperature.[8]

On the other hand, fine fibers of glass and fused silica usually show strengths ranging from a few hundred thousand pounds per square inch up to a million or more pounds per square inch. At the risk of repeating what has been rather frequently quoted, some data of Griffith and of Anderegg[1] are reproduced here (see also Fig. 1).

(1) Data from Anderegg

I. Steam-Drawn, Lubricated Fibers (Glass).

Large (0.003–0.015 in.), avg. tensile strength, 25,000 p.s.i.
Medium (0.0003–0.001 in.), avg. tensile strength, 129,000 p.s.i.

II. Flame-Blown, Fused Silica Fibers.

(0.00011–0.00020 in.), avg. tensile strength, 700,000 p.s.i.
(0.000064 in.), max. tensile strength, 2,250,000 p.s.i.

III. Silica Fibers Drawn by Bow-and-Arrow.

Large (0.00200 in.), tensile strength, 85,000 p.s.i.
Medium (0.00046 in.), tensile strength, 600,000 p.s.i.
Small (0.00015 in.), tensile strength, 3,500,000 p.s.i.

IV. Glass Textile Fibers, Average Tensile Strengths.

(0.0005 in.), 150,000 p.s.i.
(0.0004 in.), 185,000 p.s.i.
(0.0003 in.), 250,000 p.s.i.
(0.0002 in.), 400,000 p.s.i.

There naturally arises the question which has frequently been debated: To what extent are these high strength values due merely to the small size of the fibers, and to what extent may they be due to special physical peculiarities such as orientation of the molecules, perfection of surface, sudden cooling, and so on?

[7] L. G. Ghering and J. C. Turnbull, "Scratching of Glass by Metals," *Bull. Amer. Ceram. Soc.*, **19** [8] 290–94 (1940).
[8] A. Smekal, "Festigkeitseigenschaften spröder Körper," *Ergeb. Exakt. Naturw.*, **15**, 106–88 (1936); see also Preston, footnote 6.

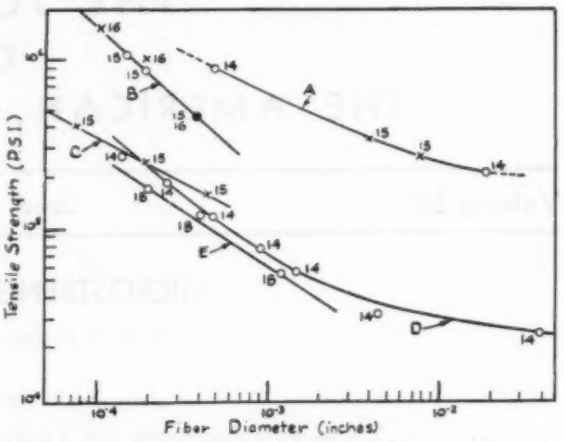


FIG. 1.—Adapted from C. J. Phillips, Glass, the Miracle Maker, Fig. 4.12, p. 86. Pitman Publishing Corp., New York, 1941; *Ceram. Abs.*, **21** [1] 11 (1942). Curve *A*, 14*, fibers pulled quickly from very hot glass; curve *A*, 15†, fibers fortified by acid polishing; curve *B*, 15 and 16‡, fibers broken in vacuum; and curves *C*, *D*, and *E*, 14, 15, and 18§, fibers not specially treated.
* A. A. Griffith, see footnote reference 1 (*a*).
† S. Jurkov, *Tech. Phys., U.S.S.R.*, **1**, 386 (1935).
‡ S. Schurkow, *Physik. Z. Sowjetunion*, **1**, 123 (1932).
§ A. Joffé and A. Walther, *ibid.*, **1**, 132 (1932).

II. Experimental Method

It has seemed to the writers that one method of throwing light on the subject might be to test the tensile strength of a minute area of a large piece of glass. This can be done by pressing a hard steel ball upon a glass surface until the surface breaks. In this case, the fracture takes the form of a "pressure cone," which forms suddenly and can be observed with a low-power microscope as a flash of light. It can also be heard as a faint "click," either by the unaided ear or

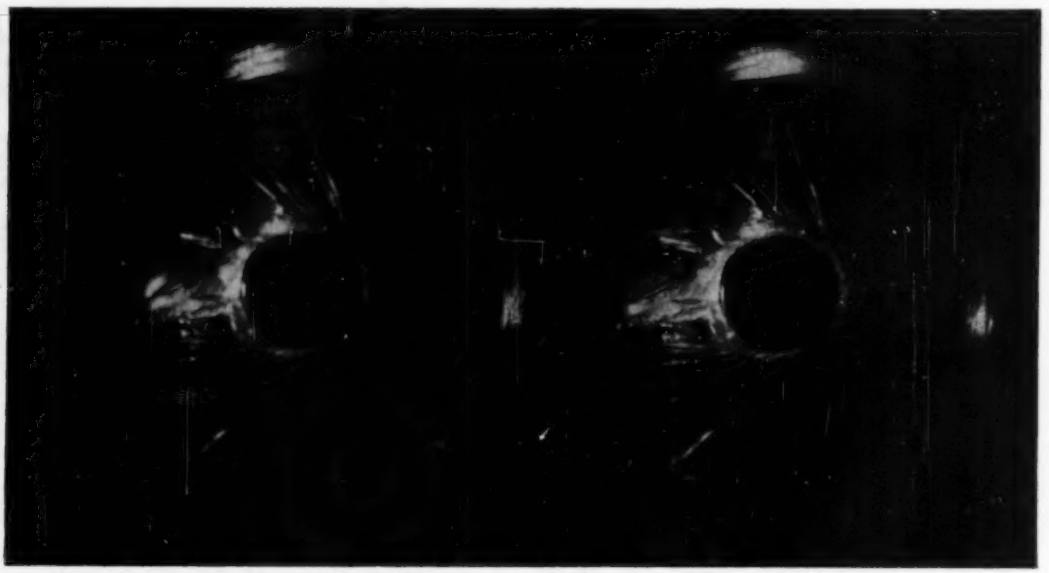


FIG. 2.—Stereoscopic view of typical "pressure cone" showing circular fracture around edge of contact circle and, deeper in the glass, larger base of cone.

TABLE I

DATA ON SAMPLES USED AND MAXIMUM RADIAL TENSION

Cones with a 1/32-in. diam. steel ball

Sample	Outside surface					Inside surface				
	N	Cones	Avg. load (lb.)	Range	σ_r (p.s.i.)	*N*	Cones	Avg. load (lb.)	Range	σ_r (p.s.i.)
Pyrex-brand beaker (0.085 in.)	3	39	15	9–20	164,000	3	30	8	6–10	133,000
1/2-gal. flint (0.120 in.)	7	100	27	16–32	201,000	5	60	42	34–48	232,000
Libbey A tumbler, wall bulge	3	26	22	20–24	187,000	3	27	30	26–32	208,000
	1	22	22		187,000	1	12	24		192,000
16-oz. flint (0.123 in.)	3	44	26	24–28	198,000	2	34	20	18–22	179,000
One-trip amber beer (0.055 in.)	2	12	15	14–16	164,000	2	8	25	24–26	195,000
Export amber beer (0.060 in.)	3	28	15	12–16	164,000	3	26	25	20–32	195,000
Window glass* (0.120 in.)	2	40	44	42–46	236,000	1	20	38		214,000
Circular plate* (0.250 in.)	1	20	14		160,000	1	20	14		160,000
Fairmont 16-oz. flint (0.120 in.)	1	16	21		184,000	1	18	30		208,000
Thatcher 16-oz. flint (0.125 in.)	1	14	30		208,000	1	16	25		195,000
6 × 1 × 1/8 laths*	7	126	46–	41–52	238,000	7	150	47+	42–52	241,000

* Flat.

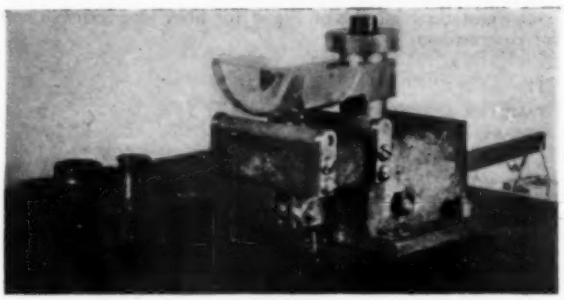


FIG. 3.—View of ball press arranged for cylindrical glass sample; observing microscope in flat plate jaw at left.

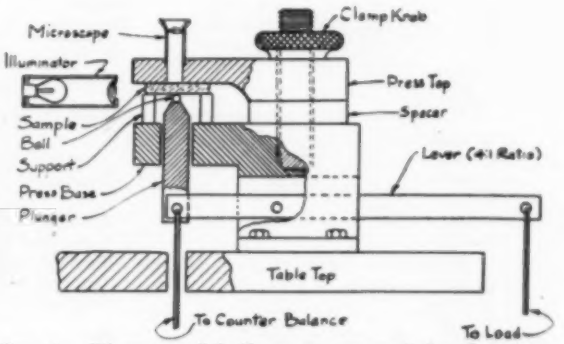


FIG. 4.—Diagram of ball press arranged for flat plate sample.

by means of a microphone. A typical "pressure cone" is shown in Fig. 2, which is a stereoscopic view.

The experimental setup is shown in the photograph of Fig. 3, and the details of the press used are more completely brought out by the diagram of Fig. 4.

The theory of the stress distribution obtained when a sphere is pressed against a flat surface was first worked out by Hertz,[9] and a brief summary is given in a convenient form by Timoshenko.[10] Because of the deformations due to the force exerted, the steel sphere and the glass plate are in contact over a finite circular area instead of the theoretical point-contact of sphere and plane. The only stress of importance here is the radial stress, which, at the surface of the glass, is a tension reaching its maximum value at the edge of the contact area.

The area subjected to this maximum tension is a very tiny one, being an annulus surrounding the contact circle. The highly stressed zone is very narrow radially and does not extend deeply into the glass, at least not until the crack actually forms. The crack occurs at right angles to this radial tension and is therefore approximately circular in shape, as shown in Fig. 2.

If the elastic constants of the glass and of the steel are known and if the diameter of the ball and the force pressing it against the glass are measured, the maximum radial tension can be calculated from the Hertz formula. This is the stress initiating the pressure-cone fracture.

Although it is true that the crack is apt to form slightly outside the zone of maximum tension, it is the value of this maximum radial tension, as computed by Hertz's formula from the data mentioned, which is recorded here as σ_r.

The highly stressed zone is comparable in area with a glass fiber. With steel balls 1/32 to 1/8 in. in diameter, the stressed annulus is of the order of 0.02 to 0.06 in. in perimeter and a thousandth inch or so in width.

III. Experimental Results and Discussion

(1) Preliminary Tests on Various Pieces of Glass and Glassware

The samples used were pieces of bottles, tumblers, and beakers, of soda-lime glass or of borosilicate, and small plates of Fourcault window glass. The samples, cut from various parts of the glassware, were suitably supported in the testing device and were tested on both the inner and outer faces of the ware. The duration of each load was approximately five seconds; in the first experiments, the ball diameter was 1/32 in.

Table I gives the number, *N*, of samples tested and their average thickness, the number of cones produced, the average load for all similar samples, and the range of these loads. Finally, it gives the calculated value of the maximum radial tension, σ_r.

[9] H. Hertz, Miscellaneous Papers, London, 1896.

[10] S. Timoshenko, Theory of Elasticity. McGraw-Hill Book Publishing Co., Inc., New York, 1934.

On some of the samples, the inside surface proves to be stronger than the outside, which might be expected in the case of container samples from their method of manufacture. However, the difference (expressed as a percentage) is not great compared with the enormous increase of strength over the values found when whole bottles or laths are tested. This macrostrength of the whole article is apt to be between 3000 and 10,000 p.s.i., as previously mentioned, while the microstrength values are in the neighborhood of 200,000 p.s.i., which is some 20 to 60 times as great.

TABLE II

VARIATION OF MICROSTRENGTH WITH BALL DIAMETER

Ball diam. (D) (in.)	Load (lb.)	d (in.)	σ_r (p.s.i.)
1/32	47	0.0080	240,000
1/16	98	0.0138	194,000
1/8	220	0.0197	160,000
1/4	168	0.0300	94,000

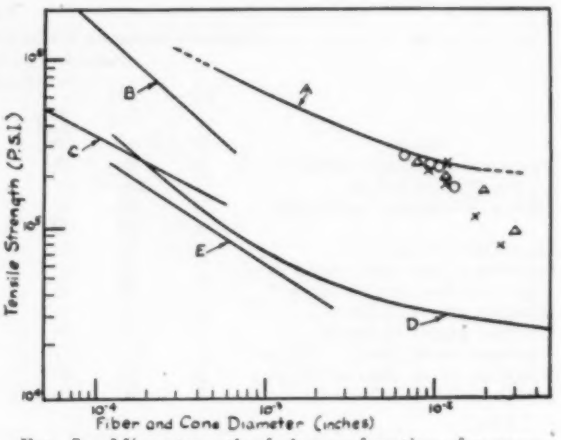


FIG. 5.—Microstrength of glass as function of pressure-cone diameter; curves of Fig. 1 for fiber strengths shown for comparison.

TABLE III

MICROSTRENGTH AS FUNCTION OF BALL DIAMETER AND SURFACE TREATMENT

Ball diam. (D) (in.)	Sample*	Surface	Avg. load (lb.)	Cone d (avg.) (in.)	σ_r (p.s.i.)
0.020	1/8 in. F	Unetched	18.2	0.0066	235,000
0.031	" " "	"	30.8	0.0082	209,000
0.031	" " "	Etched	30.7	0.0083	208,000
0.039	" " "	Unetched	36.4	0.0101	188,000
0.039	" " "	Etched	62.1	0.0109	223,000
0.063	" " "	Unetched	36.2	0.0123	138,000
0.063	" " "	Etched	58.4	0.0127	163,000
0.125	5/16 in. P	"	54.5	0.0190	100,000
0.250	" " "	"	76.5	0.0260	71,000
0.500	1 in. P	Unetched	113.0	0.0330	53,000
1.000	" " "	"	226.0	0.0520	40,000
1.250	" " "	"	377.0	0.0712	41,000

* F, Fourcault window glass; P, polished plate.

These comparatively high strength values cannot well be ascribed to molecular orientation (in the same sense as is envisaged for fibers) for the macro- and micro-strengths of the same specimen have been determined.

(2) Microstrength as Function of Area Stressed

Further evidence that the size of the area under test is the determining factor was obtained in a brief series of tests in which several sizes of steel balls were used. The specimens were Fourcault window glass, 1/8 in. thick; conditions of the test were the same as those of Table I. These results are shown in Table II. This table gives the ball diameter, D, the load in pounds, the measured cone diameter in inches, d, and the calculated maximum stress, σ_r, in lb. per sq. in.

These results show the general trend toward greater strengths for smaller stressed areas, but they are not entirely satisfactory since a 1/8-in. thick piece of glass is too thin for testing with a 1/4-in. ball.

(Table II indicates that halving the size of the ball raises the apparent strength about 50,000 lb. per sq. in.)

A more extensive series of tests has been made on flat glass samples, comprising 1/8-in. Fourcault glass, 5/16-in. polished plate, and 1-in. polished plate. The steel balls ranged from 1/2 mm. (approximately 1/50 in.) up to 1 1/4 in., a ratio of 60 to 1 or thereabouts. In this series of tests, the duration of each load was several minutes. An initial load, its value depending on the ball diameter, was first placed on the ball and the load was then increased at a constant rate such that the cone formed at the end of approximately twelve minutes.

Table III summarizes these tests. It gives the ball diameter, the type of sample, the kind of surface treatment of the sample, the average load, the measured cone diameter, d, and the calculated maximum tensile strength, σ_r.

Figure 5 shows the comparison of the results of this series of tests with the results of tests on the tensile strength of fibers. The data of Fig. 1 are repeated. Upon the same coordinates are plotted the maximum radial tension (σ_r) developed by each ball (calculated from the maximum load that the ball was able to carry at cone formation) against the diameter of the cone produced by that maximum load. The plotted points represent maximum values from the same series of tests which yielded the values shown in Tables II and III. The tensile stresses developed in producing the smaller cones (0.006 to 0.013 in. diameter) approach very closely the tensile strength shown by curve A for glass fibers pulled quickly from very hot glass or fortified by acid polishing.

IV. Conclusion

The microstrengths obtained by the pressure-cone method on large specimens are strictly comparable in magnitude with those normally obtained on fibers. This conclusion seems to establish the fact that the strength of fibers is largely due to their small size and not so much to orientation.

Acknowledgment

The authors wish to acknowledge the very substantial assistance of J. L. Glathart, who for some months past has been in charge of the work on impact at the Preston Laboratories, in getting this paper into presentable shape. The war has greatly interfered with the prosecution of our researches and in particular with writing a coherent account of them. Acknowledgment is also given to Brian Christman, now with the U. S. Army overseas, for his assistance on much of the early experimental work.

Much of the expense was defrayed by the Owens-Illinois Glass Company, through U. E. Bowes, their Director of Research, who released the results to the Glass Container Association when the latter took over the sponsorship of the general research on impact. Since the Association has now ceased to exist, the Preston Laboratories have accepted the responsibility of carrying out the intentions of the Association, namely, to make the results available to the scientific public.

PRESTON LABORATORIES
BUTLER, PENNSYLVANIA

ENERGY ADDITIVITY IN GLASSES *

BY MAURICE L. HUGGINS AND KUAN-HAN SUN

ABSTRACT

Energies of dissociation into the component ions have been computed for many simple and complex oxides. From these, 51 energy constants have been obtained, which may be used to compute approximate ionic dissociation energies in crystals and glasses in which each "metallic" atom is surrounded by oxygens. The relation of these constants to the Periodic Table is shown and briefly discussed. Slight deviations from additivity in silicates and phosphates are related to the dependence of the energy on the number of oxygens in SiO_4 and PO_4 groups which are shared with other Si or P atoms.

I. Introduction

Many of the properties of a glass can be related (1) to its internal energy or stability, a function of composition and temperature, or (2) to the magnitudes of the energy humps resisting changes in the relative positions of the component atoms. This study here is concerned with the first of these.

Strictly speaking, *free* energies should be considered, but in comparing different solids (glasses and crystals), the differences in energy are practically equal to the differences in free energy. For the present, the treatment may be simplified, therefore, by considering only energies. For accurate calculations, especially if considering temperature changes, free energies must of course be used to take account of differences in randomness.

For convenience, glasses or crystals containing only oxygen and more electropositive elements may be designated as "simple oxides" and "complex oxides." In both, according to X-ray evidence, each nonoxygen atom or ion is surrounded by oxygen atoms or ions. Most of the internal energy of a solid of this sort results from the attractions between closest-neighbor atoms, that is, from the attractions between each positive atom (Na, Ca, Si, P . . . .) and the surrounding oxygens. The number and arrangement of oxygens around a positive atom of a given element do not, in general, vary much from compound to compound or glass to glass. Approximate additivity of energies in such substances would therefore be expected, the total energy being the sum of energy contributions due to the attraction of each positive atom for its surroundings. In the calculations reported in this paper, this is shown to be the case. Significant departures from additivity, usually attributable to considerable differences in the number or arrangement of closest neighbors, are relatively rare.

For an understanding of the relative magnitudes of the forces and energies involved, it seemed best to compute energies relative to the energy of a dilute gas composed only of charged ions (Na^+, Ca^{++}, Si^{+4}, O^{--}, etc.), each ion being widely separated from the others. The requisite data for calculating E_f, the molal energies of formation from the gaseous ions, for about 50 simple oxides and approximately the same number of complex oxides are available in a valuable book by Bichowsky and Rossini.[1] From the heats of formation of the compounds and the gaseous ions, as listed by these authors, the desired E_f values can readily be computed. The equations used have been presented and discussed elsewhere by the present writers.[2]

II. Energy Constants

The E_f values, so obtained, are found to be approximately additive. For example, E_f for $CaO \cdot SiO_2$ is approximately the sum of the E_f values for CaO and SiO_2. Likewise, E_f for $2CaO \cdot SiO_2$ is approximately the sum of twice the E_f value for CaO plus the E_f value for SiO_2. The energy constants, ϵ_M, can thus be deduced for each component, each of these being the contribution to the total E_f value of one gram atom of the element M, when

* Presented at the Forty-Sixth Annual Meeting, The American Ceramic Society, Pittsburgh, Pa., April 5, 1944 (Glass Division). Received October 27, 1944.
Communication No. 998 from the Kodak Research Laboratories.

[1] F. R. Bichowsky and F. D. Rossini, Thermochemistry of Chemical Substances. Reinhold Publishing Corp., New York, 1936.

[2] M. L. Huggins and K.-H. Sun, paper presented before the American Chemical Society, Cleveland, Ohio, April 5, 1944.

TABLE I

ENERGY CONSTANTS ϵ_M IN KILOCALORIES

I	II	III	IV	V	VI
H 500					
Li 350	Be (1159)	B 2050			
Na 320	Mg 908	Al 1820	Si (3110–3142)	P (4659–4740)	S (7103)
K 275	Ca 840	Sc (1563)	Ti (2882)	V (4564)	
Rb (269)	Sr 790	Y (1564)	Zr (2636)		
Cs (262)	Ba 755				
Cu (295)	Zn 940	Ga (1827)	Ge (3055)	As (4443)	
Ag (359)	Cd (913)	In (1722)	Sn (2823)	Sb (4212)	
	Hg (933)	Tl (1734)	Pb (2832)		
Hg (378)					
		As (1768)			
	Sn (886)	Sb (1660)			
Tl (314)	Pb (842)	Bi (1583)			
	V (901)	V (1691)			
		Cr (1728)			
	Mn 909				
	Fe 932				
	Co (1147)				
	Ni (964)				
	Cu (892)				
	Pd (1006)				

in its usual oxygen environment. Otherwise expressed, for a compound or glass of formula $M_aM'_{a'}M''_{a''}\ldots\ldots O_b$, the molal energy of formation from the gaseous ions is given by equation (1).

$$E_i = \sum_M a_M \epsilon_M \qquad (1)$$

The ϵ_M values are listed in Table I.

For some of the components, the ϵ_M values deduced from complex oxides (by subtraction of the contributions of the other components) differ appreciably, though not greatly, from the corresponding values computed from the E_i values for the simple oxides. In such cases, the ϵ_M values given are those deduced from the data on complex oxides. In some instances, these were glasses; in others, crystals. The values given in parentheses were obtained from the simple oxides only.

If the coordination number of the M atoms in a given compound or glass is known, the ϵ_M value can be divided by that coordination number to obtain what might be called a "contact energy," an energy magnitude associated with a single metal-oxygen contact. These contact energies are comparable to the bond energies often discussed for molecules and crystals in which the atoms are joined together by definite electron-pair bonds. Contact energies are additive and transferable from compound to compound (or glass), provided the coordination numbers do not change. In view of the incomplete knowledge of the coordination numbers of the elements in many structures, however, contact energies are, at present, less generally useful than the ϵ_M values.

Most of the ϵ_M values which have been computed by the authors are shown in Fig. 1, plotted in such a way as to indicate the relationship to the Periodic Table. As would be expected, the magnitude of ϵ_M is determined primarily by the ionic charge on M. The greater the charge, the greater is the attraction energy. Next most important is the distance between the centers of adjacent M and O atoms (ions). In general, for each group of elements in the Periodic Table, the attraction

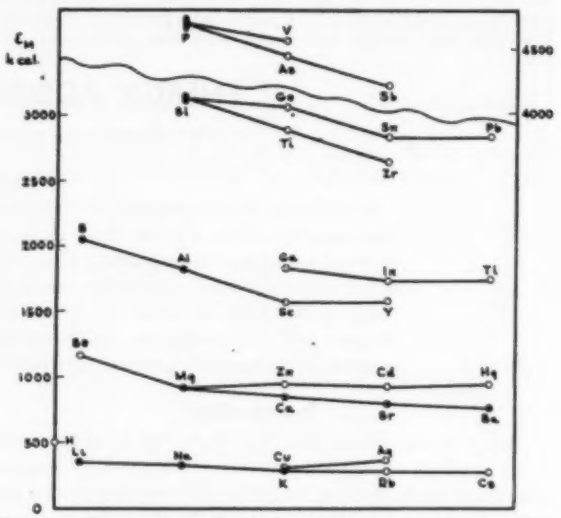


FIG. 1.—Energy constants, ϵ_M, plotted so as to show the relationship to the Periodic Table.

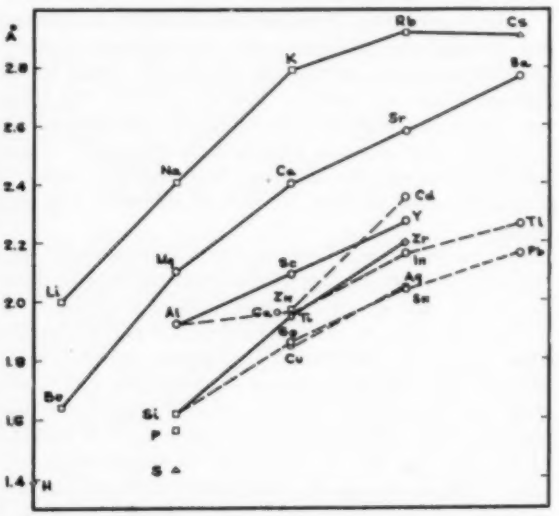
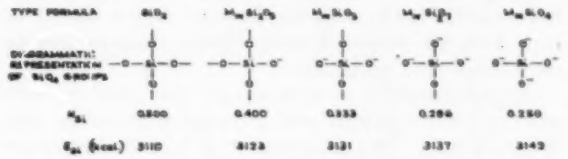


FIG. 2.—Interatomic distances in oxides, plotted so as to show the relationship to the Periodic Table.

energy constant *de*creases as the atomic number and atomic weight *in*crease; whereas, as shown in Fig. 2, the interatomic distance *in*creases as the atomic number of the more positive element *in*creases.

TABLE II

VARIATION OF ϵ_{Si} WITH COMPOSITION FOR SILICATES



III. Variability of ϵ_M Values in Silicates and Phosphates

For silicates, the data show a slight trend in the ϵ_S value with the ratio of Si to oxygen in the compound or glass. If, as an approximation, each Si is considered to be joined to its four neighboring oxygens by chemical bonds, but if the attractions between the oxygens and other more positive elements are considered to be ionic, the data indicate an increase in ϵ_{Si}, and hence in stability, on going from left to right in the series shown in Table II.

Equation (2) satisfactorily represents the data; N_{Si} denotes the number of silicon atoms per oxygen atom.

$$\epsilon_{Si} = 3174 - 128\ N_{Si} \qquad (2)$$

The values of ϵ_{Si} obtained for these different classes of silicates confirm the idea, which the writers have previously expressed,[3] that, for greatest stability, SiO_4 groups of types which are not adjacent in this series will not coexist side by side in the same glass or crystal. For example, silica (SiO_2) and an orthosilicate, such as Na_4SiO_4, would tend to react together, giving (if in equivalent amounts) a metasilicate, Na_2SiO_3. This would be predictable from the figures just given, since 3110 plus 3142 gives 6252, which is less than twice 3131. The writers consider this to be a very important principle.

Similar relationships to those just discussed for silicon-containing compounds can be shown to apply also to the phosphates. Equation (3) fits the data reasonably well.

$$\epsilon_P = 4875 - 540\ N_P \qquad (3)$$

IV. Conclusion

This work constitutes a step toward a better understanding of the relationships between the internal structure and the composition of glasses (and crystals) and between the internal structure and the properties of the bulk materials. Much more, obviously, remains to be done.

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ROCHESTER 4, NEW YORK

[3] (*a*) M. L. Huggins, K.-H. Sun, and A. Silverman, "Vitreous State," *Jour. Amer. Ceram. Soc.*, **26** [12] 393–98 (1943).

(*b*) M. L. Huggins, K.-H. Sun, and A. Silverman, "Vitreous State" in Colloid Chemistry, Theoretical and Applied, Vol. V, edited by J. Alexander. Reinhold Publishing Corp., New York, 1944.

CONTINUOUS TANK FOR HAND-BLOWN GLASS*

BY F. G. SCHWALBE

ABSTRACT

The quality of glass obtainable from a continuous glassmelting furnace is dependent on raw materials, fuels, furnace design and operation, and skill in the art of gathering and manipulating molten glass. Of these requirements, the content of the present paper is limited to information on furnace design and construction and its effect on the ultimate quality of the glass that can be produced when proper fuels, raw materials, and labor are employed.

I. Introduction

(1) Type of Glass and Furnace Design

The first design consideration is the kind and quantity of glass that is to be melted. The quantity of glass required determines the melting area of the furnace and this, in turn, determines whether an end-port or side-port furnace should be selected. The area required in the melting end of a continuous tank depends on the type of glass that is to be melted. The following values† may be assumed for general purposes:

	Sq. ft./ton
Soda-lime crystal	8–12
Lead glass	8–12
Colored soda lime	8–12
Borosilicate for pressed ware	11–15
Borosilicate for thin blown ware	16–21

When the tonnage of glass to be produced is known the area of the melting end of the required furnace may be determined. The next step is to determine the type of furnace that will produce, economically, the desired amount of glass.

The curve shown in Fig. 1 is helpful in making this selection because it indicates the holding heat in B.t.u. per hour required per square foot of melting tank area for furnaces of different capacities. Up to 300 sq. ft. melting area, the curve shows values applying to the holding heat on end-port design furnaces. Above 300

* Forty-Seventh Annual Program, The American Ceramic Society, 1945 (Glass Division Supplementary Title). Received March 19, 1945.

† The melting area for borosilicate ovenware-type glass depends on whether the glass is to be used for making pressed or thin blown articles.

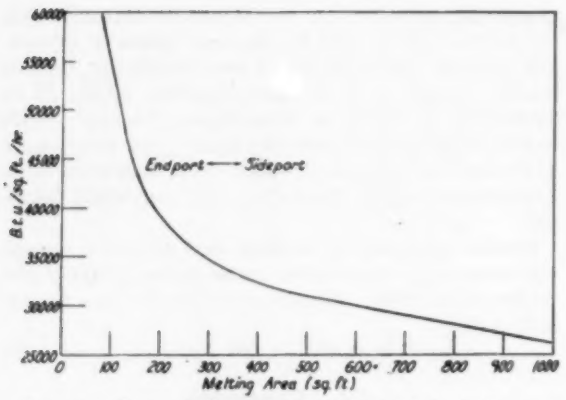

FIG. 1.—Curve indicating holding heat in B.t.u. per hour per square foot of melting tank area for furnace of varying capacities.

sq. ft. melting area, the side-port design is selected. If the side-port design were used for furnaces with a melting area of less than 300 sq. ft., the holding heat per square foot would be far in excess of that indicated for the end-port design.

For values of holding heats, the furnace in question may be assumed to have a clay lining, to be of the regenerative type, and to be new. Inasmuch as the actual quantity of fuel required to do the melting can be taken as a fixed amount per ton of glass melted, regardless of furnace size, the deciding factor in the selection of furnace type and size is shown clearly in Fig. 1. This figure shows how rapidly the holding heat values increase on furnaces of 200 sq. ft. or less in melting area.

The next factor is the depth of the furnace, which is governed also by the type of glass to be melted, and may be tabulated as follows:

	Depth (in.)
Soda-lime crystal	36
Lead crystal	30–36
Borosilicate for ovenware	36
Colored soda lime	Variable

Holscher[1] has presented data useful for determining the depth of furnaces to be used for melting colored soda-lime glasses. He has tabulated the results of experiments to determine the temperature gradients existing in different colors of soda-lime glasses.

The design of furnace throats is fairly well standardized, and the conventional straight-through design is used in most cases. A drop or submarine throat may be used in soda-lime crystal glassmelting furnaces.

Only the regenerative furnace is mentioned here because it is the most universally used design. Recuperators may also be used for furnishing preheated air for combustion. Direct-fired furnaces are used in some cases, although they are inefficient and cannot be credited to be good glass producers.

The refractories used for melting the best crystal glasses require the lowest possible iron content.

[1] H. H. Holscher, "Experimental Studies of Temperature Gradients in Glasses of Various Colors," *Jour. Amer. Ceram. Soc.*, **26** [12] 398–404 (1943); a similar paper was presented at the Seventh Conference on Glass Problems, University of Illinois, November, 1944.

II. Furnace Temperatures and Pressures

Temperature distribution within a furnace should have careful study, and the furnace design should be such that the required temperature g adient can be established and maintained.

Optical readings were taken on the glass on both sides of the bridge wall, and, although they are general, they will suffice for the discussion of furnace design and show how such figures are established and maintained.

	Optical on bridge (°F.)	
Glass	Melting end	Working end
Crystal soda lime	2560	2350
Lead crystal	2550	2300
Borosilicate	2850	2650

These working-end temperatures are usually obtained by building a shadow wall on top of the bridge wall. The design of the shadow wall must be such that it will permit only the proper amount of heat to radiate and waste gases to circulate through the working end of the furnace.

In an end-port furnace, the shadow wall must hold back the heat, which is directed squarely at it from the end ports (see (*A*), Fig. 2).

In the side-fired furnace, the effect of the fire is less severe on the shadow wall (see (*D*), Fig. 2). With skill and experience gained in operating furnaces, it is possible to design a shadow wall to give the best results under average melting conditions. The first difficulties are encountered when an attempt is made to increase the melting rate of the furnace, necessitating higher melting temperatures. It is common practice to adjust the furnace pressure to give the desired working end temperature. The furnace pressure should be adjusted to give maximum thermal efficiency consistent with the production of good glass and not to control the working end temperature.

Figure 2 (*A*) shows a conventional end-port furnace and (*D*), that of a side-port furnace. Both plans indicate the use of a conventional shadow wall built on the bridge wall; Fig. 2 (*B*) shows a modification, also applicable to side-port furnaces. The working end, (*B*) is independent of the melting end and is separately heated. The design permits temperature control in the working end, independent of the melting end, and also maintenance of proper furnace atmosphere and pressure. This feature is valuable for lead glass production because it permits a reducing flame in the melting end and an oxidizing atmosphere in the working end. When finished glasses are susceptible to contamination by impurities in the fuel, this design permits the use of better fuel in the working end than that in the melting operation.

The fact was mentioned that furnace pressures are changed when melting rates are altered. Automatic furnace-pressure regulation obviously can be used to maintain a given set of conditions, but the desired new set of conditions must be manually reset when the rate of pull is increased or decreased. Such a change in furnace conditions affects the air supply being introduced into the furnace whether natural draft or fan air is being used. The quantity of fan air may be

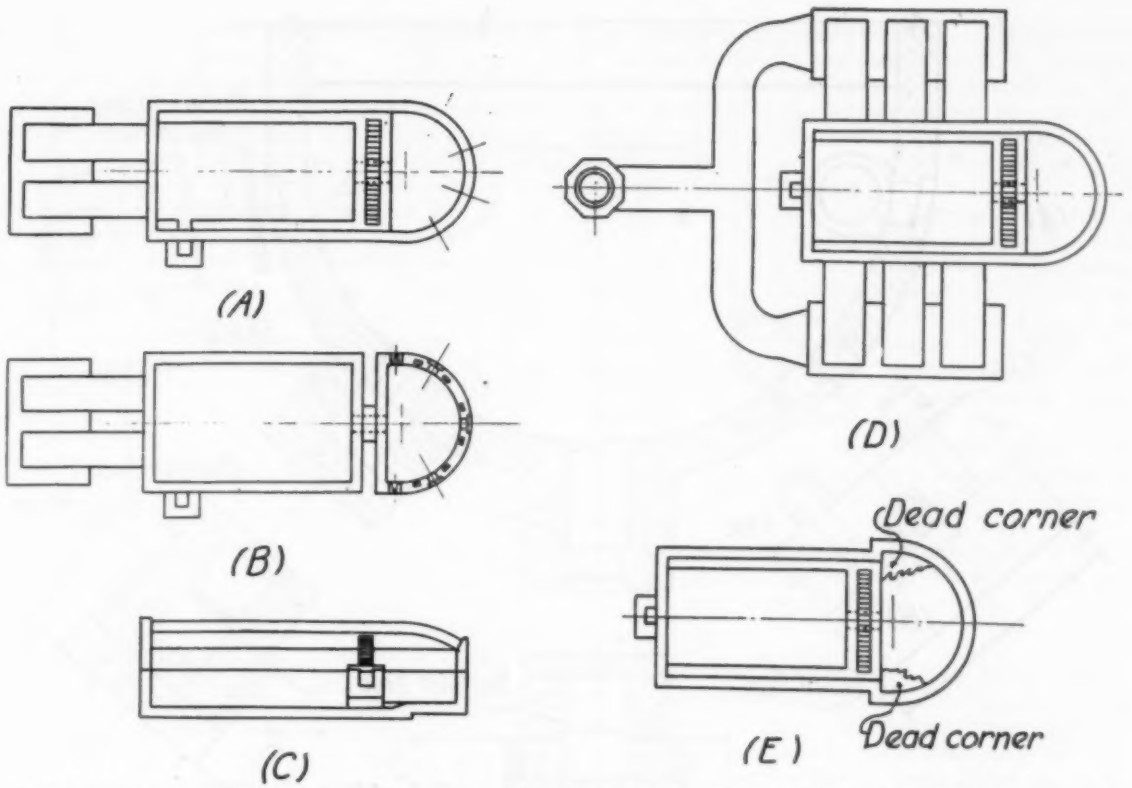

FIG. 2.—(*A*) Plan of conventional end-port furnaces in which shadow wall must hold back heat directed squarely at it from end ports; (*B*) modification of (*A*), also applicable to side-port firing; (*C*) working end of furnace having less depth than at working end; (*D*) side-fired furnace showing less severe effect of fire on furnace wall; (*E*) design showing dead corners at working end.

affected by as much as 5 or 6%; in the case of natural draft, the error is considerably greater.

The adoption of a separately heated working end on the furnace does not necessarily solve the problem of temperatures. Figure 3 shows various types of gathering arrangements, each adaptable to a specific application. Most glass manufacturers use as little clay in the glass as possible to reduce the formation of cords and seeds. Another approach to this problem is the use of a working end of less depth than the melting end, see Fig. 2 (*C*). The purpose of raising the bottom in the working end is to reduce the volume of glass to a minimum.

The number of work openings required determines the working end dimensions. Under no conditions should the working end be designed with dead corners as shown in Fig. 2 (*E*).

III. Gathering Openings

Figure 3 (*E*) shows the ideal opening because no clay is used in the glass. With this opening, a definitely plus furnace pressure must be maintained to prevent gathering threads from entering the furnace. To permit working under a plus furnace pressure into an open tank, a water-cooled shield may be used that will afford protection to the gatherer. This design has the disadvantage that only one temperature of glass can be gathered, making it necessary to limit all shops to one glass temperature regardless of the type of ware being made. A second disadvantage is the fact that the gathering chills have a tendency to move from one gathering opening to another.

Figure 3 (*A*) shows how glass at various temperatures may be gathered; a full ring of any desired depth may be anchored to the flux wall by suitable means and may be easily replaced.

Figure 3 (*B*) shows the conventional type of gathering boot with the addition of flues installed in the breast walls adjacent to the side of the gathering boot. These flues permit heat circulation from the surface of the glass. Figure 3 (*C*) shows a modification of the scheme (*E*), which as described has the shortcoming of providing no temperature variation necessary for various gathering operations. The diagram (*C*) consists of an extension to the working end of the furnace. The extension sides may be insulated, and a burner is provided to condition the glass in the extension suitable for any desired gathering operation.

Figure 3 (*D*) is similar to (*C*) except that the extension is independent of the working end of the furnace. The glass is fed to the extension through a throat. A burner is provided to permit proper conditioning of the glass. This design is good where it is desired to hand

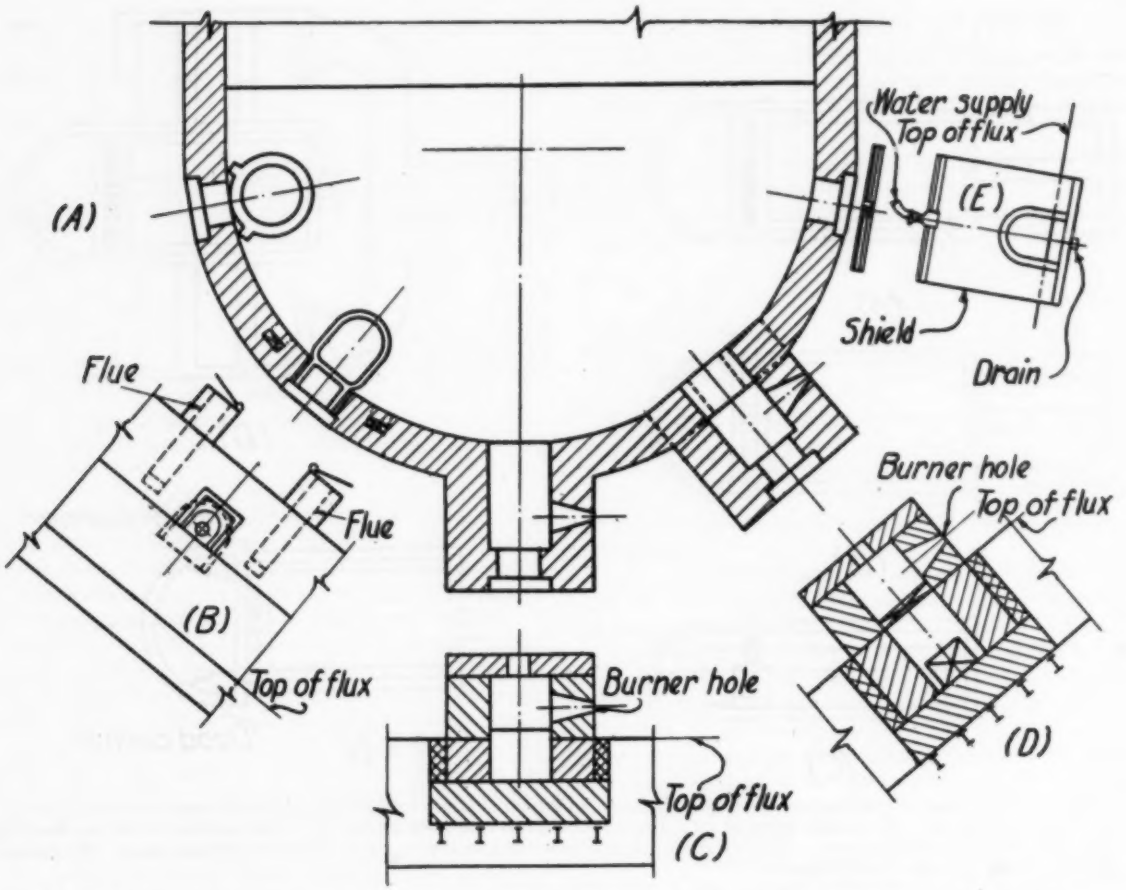

FIG. 3.—(*A*) Plan to permit various temperatures of glass to be gathered; (*B*) conventional type of gathering boot; (*C*) extension of working end of furnace, modification of scheme shown in (*E*); (*D*) similar to (*C*) except that extension is independent of working end of furnace; (*E*) ideal opening because no clay is used in the glass.

gather from a working end supplying glass to automatic feeders and machines.

IV. Instrumentation

Perfection of quality requires an exact knowledge of conditions as they exist within a melting furnace. Glass manufacturers take great pains in the selection and blending of the raw materials for making glass. The same care should be exercised in the operation of the melting furnaces. Instrument manufacturers have available equipment at reasonable costs to take care of the important phases of melting.

(1) Fuel Meters

All fuel meters should record, integrate, and indicate the amount of fuel being introduced into the furnace. Certain fuels, such as producer gas, offer metering difficulties if the furnace is taking fuel from a common line supplying two or more furnaces.

Fuel-oil meters should be provided with a large dial that will permit clocking to obtain the rate of fuel input into the furnace. Such meters are available at small cost. The metering of natural and artificial gases offers no problem.

(2) Air Meters

All furnaces should be provided with a fan to insure a uniform flow of combustion air at a pressure that will permit metering. Adjustment of fuel and combustion air by means of meters is preferable to the use of flue-gas analysis. Such analyses are usually subject to errors as a result of the dilution with batch gases. Flue-gas analysis, however, is recommended to determine whether complete combustion is taking place.

(3) Temperatures

No comment is necessary on instruments for indicating and recording furnace and glass temperatures. A wide choice of instruments is available. There is a new radiation intensity recorder which, when directed to a flame or incandescent body, will record the intensity of radiation in percentage of that of a black body. This device has shown some interesting results when used in open-hearth operations. It should also be useful on furnaces in which the atmosphere and the radiating properties of the flame affect the color of the glass.

(4) Furnace Pressure and Glass Level

The importance of maintaining furnace pressure has

been discussed; a wide selection of instruments is available for this purpose.

The glass-level phase of furnace operation is important because it vitally affects the operation of automatic machines. Variations of tank level at high melting ratio seriously affect the glass quality. It is quite evident that such variations will also affect the quality of the glass in the hand-blown tank operation. The visible affect on quality may be less evident than in machine operation because of the lower melting ratio used in hand-blown tank operation. The fact, however, that the standards of quality for hand-blown glass are high makes any small change in quality noticeable.

All furnaces should be equipped with a recording glass-level gauge that will continuously record and indicate the trend of the glass level. A device of this kind can be utilized to control the operation of batch feeders if such equipment is installed.

V. Batch Charging

Because the average glass requirements for hand-blowing operations are usually low as compared with automatic machinery operation, such furnaces are generally charged by hand. The method of charging requires careful study. The tendency of automatic chargers to spread the batch to a thin layer makes necessary an increase in the amount of decolorizer that must be used. It is logical to assume that the same thing might happen to the coloring agents when colored glasses are being made.

VI. Application of Fuels

The secret of good furnace design lies in its adaptability to fuels. The application of fuel must be such that the following points may be accomplished with an increase or a decrease in the melting rate: (*a*) a clean fire, (*b*) proper temperature gradient within the furnace, (*c*) proper furnace atmosphere, (*d*) flame coverage of melting end, and (*e*) combustion occurring within the furnace. These requirements can be fulfilled with various types of fuel now in common use.

(1) Producer Gas

Because of the difficulty of regulating the flow of hot producer gas, the distribution of the fuel in a side-fired furnace depends on a set of conditions fixed by the furnace port design. Changes in port design can be made only at the time of furnace repairs, and for this reason particular care must be taken in the design of producer gas ports. With proper port design, a clean fire can be obtained; this is also effective in establishing the proper temperature gradient and furnace atmosphere. To obtain flame coverage of the melting end with producer gas is a simple matter because of its low heating value. The control of combustion so that all of the gas burns within the furnace is sometimes a difficult task because only one major adjustment is possible, namely the combustion air.

(2) Natural Gas

Natural gas is the ideal fuel for glassmaking because of its cleanliness and ease of handling. The application of the gas to the furnace can be made by its introduction to burners firing at an angle through the sides of the ports. The gas usually is fired at a pressure ranging from 10 to 24 ounces. This application of gas usually results in a sharp fire that does not give the maximum furnace coverage.

High-pressure firing has gradually given way to the use of low pressures wherein the gas is introduced at right angles to and through the sides of the ports. This gas discharges in front of a baffle built above the port floor. The gas entering the ports in front of the baffles forms into an incandescent layer which discharges into the furnace as a soft flame affording maximum glass surface coverage. This system has many advantages, lending itself to high production and economical operation. Inasmuch as this type of firing requires a pulling action or draft to carry the flame across the width of the furnace, its use is restricted to side-port firing.

For end-port furnaces, firing a combination of above and below the ports offers flame-length control and maximum glass-surface coverage.

(3) Fuel Oil

Fuel oil may be used successfully on either the end-port or side-port type furnaces. The application on end-port furnaces should be above and below the ports. For side-port furnaces, the use of fuel below the port is by far the best method of burning fuel oil. This application, however, requires a furnace of special design and cannot be used on existing furnaces without a great amount of redesigning and reconstruction. As a second choice, the use of fuel oil above the ports will give excellent results. Such an application can be made on most existing furnaces.

A combination of top and bottom firing is in use but is not recommended except on new designs.

Firing through the back wall of the side-port furnace is also in use and is satisfactory up to 450 sq. ft. of melting area. For end-wall firing, high-pressure compressed air or steam atomization is satisfactory. Low-pressure 20- to 30-ounce air can also be applied for atomization. The application of low-pressure type burners for side-port firing has the disadvantage of requiring large burner openings.

The selection of oil-burner equipment is not the purpose of this paper. Each burner manufacturer has something to offer which he considers better than that of his competitor. The important thing is the selection of a burner that has sufficient capacity, offers flexibility, and is simple in design and construction.

VII. Conclusions

This paper has been prepared as a stepping stone to further discussion. Any one of the various points covered herein can be elaborated on at great length and each offers an opportunity to help manufacturers of hand-blown glass.

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METHOD FOR THE CREATION OF GEOMETRIC DESIGNS BASED ON STRUCTURE*

By Edwin M. Blake†

Abstract

The method described is based on a study to discover, collect, and classify the geometrical figures and ideas of value to artists and designers in the field of geometric or abstract art. The program includes modeling and sculpture and drawing and painting, with their applications to pottery design and decoration, and also abstract "movies." The basis of the method is the concept of structure introduced into geometry in 1847. This geometrical structure is similar to the anatomical structure of the human hand in that one structure is capable of assuming a great variety of forms. In making a surface design, for example, the designer selects a line structure that seems to be suitable. This consists of a definite number of lines connected in definite ways but is otherwise free to take any form. The designer endeavors to throw the selected structure into a satisfactory form. To assist him are types of curves and angles suggestive of what is possible. Having a given number of lines and their connections, specific form, to be determined by the designer, is stimulative of creative activity. If variations of color over domains (areas) are to be employed, they can be designed as accurately as any other feature.

I. Introduction

This paper is in the nature of a report of progress of an undertaking that has engaged the attention of the author for many years past and which is not yet completed. This study is to discover, collect, and classify the geometrical figures and ideas that would seem to be of value to artists and designers in the field of nonnaturalistic art, whether they work in the field of fine or applied art, that is to say, art that does not employ plant and animal forms, the human figure, and landscapes.

The basis for the classification of figures is their structure, an idea that was introduced into geometry by Listing as recently as 1847. An anatomical example of structure is the human hand, which has the same number and kinds of bones, muscles, arteries, veins, and nerves, connected together in the same ways, whether the hand is open, closed, or in any other of the shapes of which it is capable. Whatever be the form of the hand, its underlying structure remains the same. Examples of geometric structure will be shown later.

In collecting geometrical material for a method of design, it is impossible to include all geometric figures and ideas. There are many beautiful quantitative relations between parts of figures or between two or more figures that calculation reveals but the eye cannot see. Obviously, only those characteristics of a figure that can be seen contribute any esthetic value to a design in which the figure is used.

The greater the number of kinds of figures that a method of design makes available, the greater the variety and number of designs an artist may make but the greater the difficulties in learning and using the method. The method must be based on a happy mean between extremes. Music has its definite pitches, intervals, and scales; it does not employ all sounds. The author, for example, has excluded from sculpture both wire and transparent surfaces, although both of these features are present in much modern work. Many modern nonnaturalistic paintings show one rectangle lying across another, the upper one transparent. This transparency also has been excluded from the method under description.

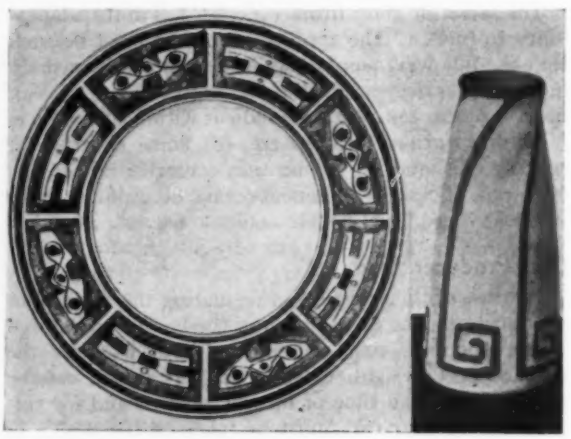

Fig. 1.—*Left*, plate design by E. M. Blake; *right*, decorated vase.

II. Scope of Method

The method of design presented herein provides motives and ideas for the following arts, both fine and applied, all of them arts of pure, nonnaturalistic, or geometric form.

(1) Plastics

Plastics cover modeling and sculpture, both in the round and bas-relief, including statuary, plaques, architectural ornament, and pottery.

* Forty-Seventh Annual Program, 1945 (Design Division supplementary title). Received March 31, 1945.

† A photograph and biography of author will appear in the June 1945 issue of *The Bulletin*.

FIG. 2.—Spanish tile, XVI century, Louvre, Paris.

FIG. 3.—Knot by Blake (crack across negative).

(2) Graphics

Graphics include drawing and painting as fine art; easel paintings, etchings, and lithography; and, as decorative art, designs for pottery and textiles. According to the depth represented perpendicular to the surface on which a drawing or painting is made, there are three varieties of graphic art, (*A*) presentive, (*B*) laminate, and (*C*) depictive graphics, each capable of being used as fine or as decorative or applied art.

(*A*) *Presentive Graphics:* No depth is represented; the drawing or painting is its own original; it does not represent or depict anything else. Such a work brings a concept or idea directly before the mind; examples are a plate design and a decorated vase (Fig. 1).

(*B*) *Laminate Graphics:* This group includes interlaced, braided, and knotted patterns and designs employed in the borders of Roman mosaic pavements of the first and second centuries A.D. and in much of Celtic and Mohammedan art. The name "laminate" refers to the fact that the drawing or painting is a representation or depiction of an original composed of laminae, that is to say, thin sheets lying across one another. The original is a very thin, flat structure laid on a background surface, and the laminate drawing or design shows it as a thin thing laid flat. The depth shown is only sufficient to permit a thin sheet of material to pass under or over another. Figure 2 is a Spanish tile of the XVI century showing a braided pattern, and Fig. 3 is a water color of a knot.

(*C*) *Depictive Graphics:* Depictive graphics include still-life paintings, drawings, and designs of geometric plastics (see section II (1)) and grapho-plastics (see Section II (3)). The problem here is to obtain and arrange the objects that are to be painted. Such drawings and paintings show full perspective depth perpendicular to the plane of the canvas or piece of pottery on which they are executed. Figure 4 shows a

FIG. 4.—Japanese dish, Metropolitan Museum of Art, New York.

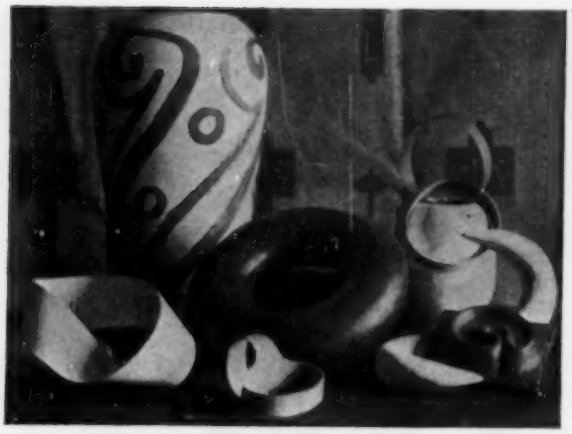

FIG. 5.—Depictive graphic composition.

FIG. 6.—Cypriote vase of early Iron Age, Metropolitan Museum of Art, New York.

Japanese dish, the central hexagon of which is occupied by a landscape, an example of naturalistic depictive art. When this landscape is replaced by a painting of a group of nonnaturalistic objects, such as those in Fig. 5, an example of geometric depictive graphics results.

(3) Grapho-Plastics

In grapho-plastics or polychromatic sculpture, the creator of such a work has two problems, (1) the creation of a plastic form and (2) its decoration by an appropriate graphic composition. When the surface to be decorated is a piece of paper or canvas, a dinner plate, or other simple surface, the result falls under graphics—no plastic form has been created. Not many illustrative examples are available. Doubtless,

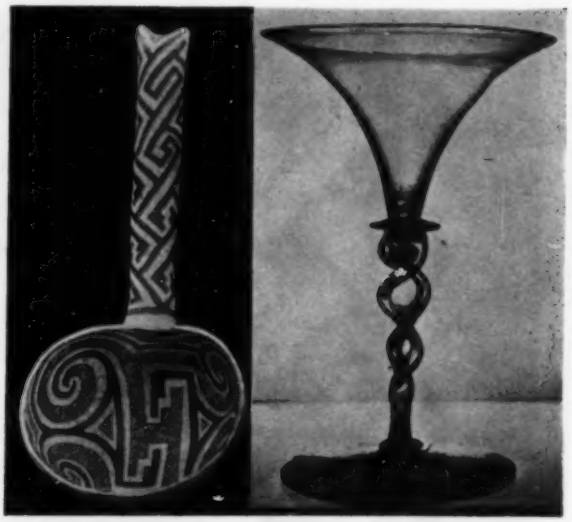

FIG. 7.—*Left*, Tulurosa pottery ladle, New Mexico (American Museum of Natural History, New York); *right*, Venetian wine glass (Metropolitan Museum of Art).

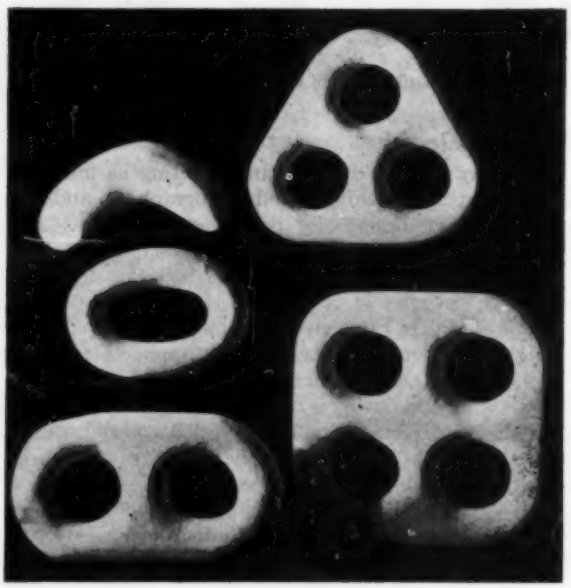

FIG. 8.—Ovoid, annuloid, triannuloid, tetrannuloid, and pentannuloid (models by Blake).

the Cypriote vase, Fig. 6, was considered a meritorious plastic creation when it was made some twenty-five to thirty centuries ago, and its graphic decoration admirably fits it. The Indian ladle, Fig. 7 (*left*), is another example of grapho-plastics.

(4) Mobile Graphics

Mobile graphics or geometric "movies" employs the technique of the animated cartoon so successfully used by Walt Disney. Most of those the author has seen were shown at the Solomon R. Guggenheim Museum in New York, but from a design standpoint they leave

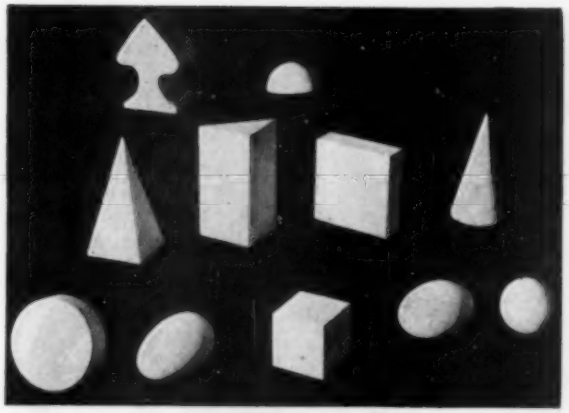

FIG. 9.—Forms of the ovoid.

FIG. 10.—Pitcher.

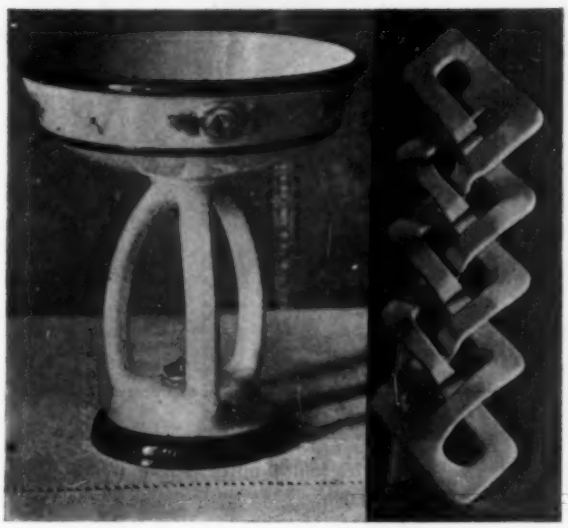

FIG. 11.—*Left*, compote, a form of triannuloid; *right*, braided triannuloid (model by Blake).

much to be desired. Mobile graphics are also of the same three kinds as graphics, namely, (*A*) presentive, (*B*) laminate, and (*C*) depictive. It is possible to have the character of a composition change during its delivery. The author believes mobile graphics accompanied by music has a great future.

(1945)

FIG. 12.—*Top*, tetrannuloid (model by Blake); (*correction:* cut should be turned 90 degrees to illustrate its proper position); *bottom*, vase, form of tetrannuloid.

III. Fundamental Surfaces and Their Modifications

Surfaces are necessary for sculpture, for graphics, and for grapho-plastics, and drawings and painting cannot be accomplished without having a surface on which to work, whether it be simply a piece of paper or a gracefully formed vase. The surfaces on which this method of design is based are an endless series called the fundamental surfaces and their various modifications. Figure 8 shows the first five fundamental surfaces beginning with the simplest, the "ovoid" (upper left). The term ovoid does not mean a specific form of surface; it is a structural term, meaning a closed surface having no opening or hole through it. Figure 9 shows several other forms of the ovoid. With a ball of modeling clay, any form into which it can be made is a form of ovoid, provided no hole is made through it. Although, perforce, models are usually made of solid material, such as clay, wood, or plaster, it is only the thin outer surface or skin of the model that is the ovoid or other surface as the case may be.

The surface below the ovoid in Fig. 8 is the annuloid, which again is a structural term. Any closed surface with one opening through it is a form of annuloid. Any form that can be made from a piece of modeling clay that has one, and only one, opening through it is an annuloid. The pitcher (Fig. 10) is an annuloid; the one opening through it is under the handle, but the recess inside the pitcher is not a hole through. The Venetian wine glass, Fig. 7 (*right*), is also an annuloid.

The next three fundamental surfaces (see Fig. 8) are the triannuloid having two holes through it, the tetrannuloid having three, and the pentannuloid having four, all terms meaning structure, not specific form. The compote, Fig. 11 (*left*), is a triannuloid, as is also the braided surface (Fig. 11, *right*). Figure 12 (*top*) is a tetrannuloid, as is also the vase with three handles, Fig. 12 (*bottom*). The vase, Fig. 13 (*top*), having four handles is a form of pentannuloid.

Besides these surfaces being hollow, it is assumed that they may be stretched or shrunk to any desired extent. One way of modifying any fundamental surface, except the ovoid, is to stretch one of its tubular parts to make it of sufficient length, cut the tube across, make a knot in it, and then rejoin the cut edges. Figure 13 (*bottom*) is an annuloid that has received a knot of five crossings.

The greater part of the pottery that is sufficiently fine to be set apart to be looked at consists of plates and vases decorated with naturalistic subjects and figurines. It would seem that some of these plates and vases might receive good geometric designs and that an equivalent of the figurine might be produced by decoating some of the forms of the fundamental surfaces, producing examples of grapho-plastics.

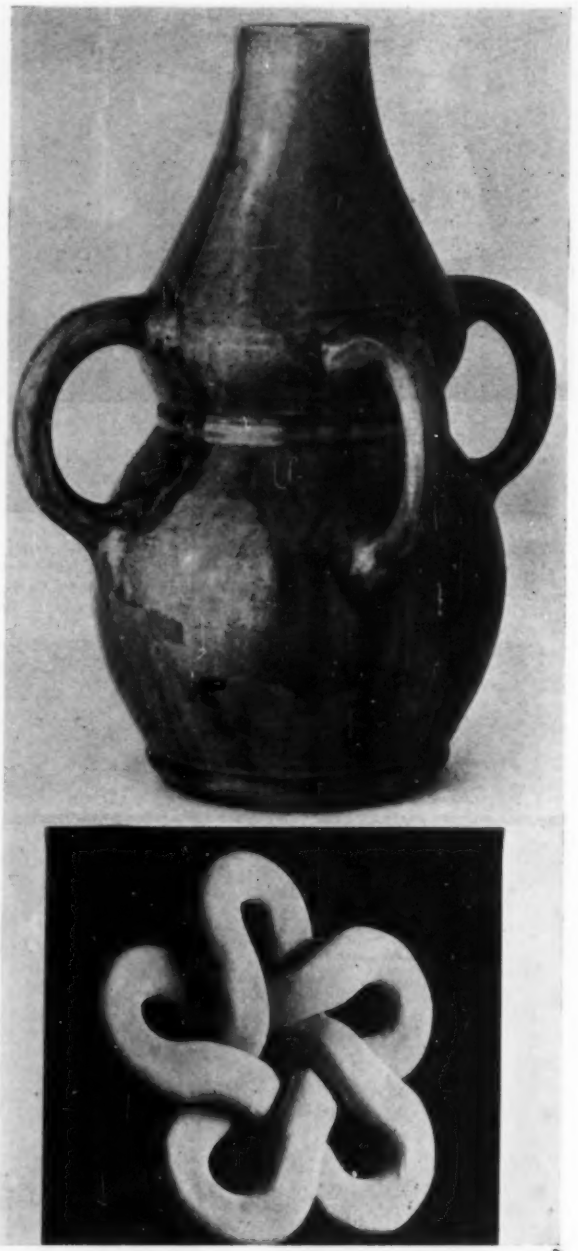

FIG. 13.—*Top*, vase with four handles, a form of pentannuloid; *bottom*, annuloid with five crossings (model by Blake).

IV. Elements of Presentive Graphic Structure

In section II, it was stated that geometric graphic designs may be classified under three types. To the first of these, presentive graphics, the kinds of figures that make up its subject matter from a structural point of view are considered. Form will receive brief consideration later. Structurally, there are three kinds of lines: biterminals, two ends; aterminals, no end; and uniterminals, one end as shown in Fig. 14. Numbers 1 (*a*) to 1 (*i*) are biterminals as are also Nos. 4 (*a*) to 4 (*e*). The objection may be raised that No. 4 (*e*) is composed of nine straight lines joined end to end, which is true in speaking of form; but as a structure, No. 4 (*e*) is a line or path running from *A* to *J*. These biterminals stand alone and have two end points each; No. 5, however, is also composed of biterminals; some, such as *CA* and *CB*, have one end point each and the other terminal of each is the junction *C*; biterminal *CD* runs from junction *C* to junction *D*. Numbers 8 (*a*) to

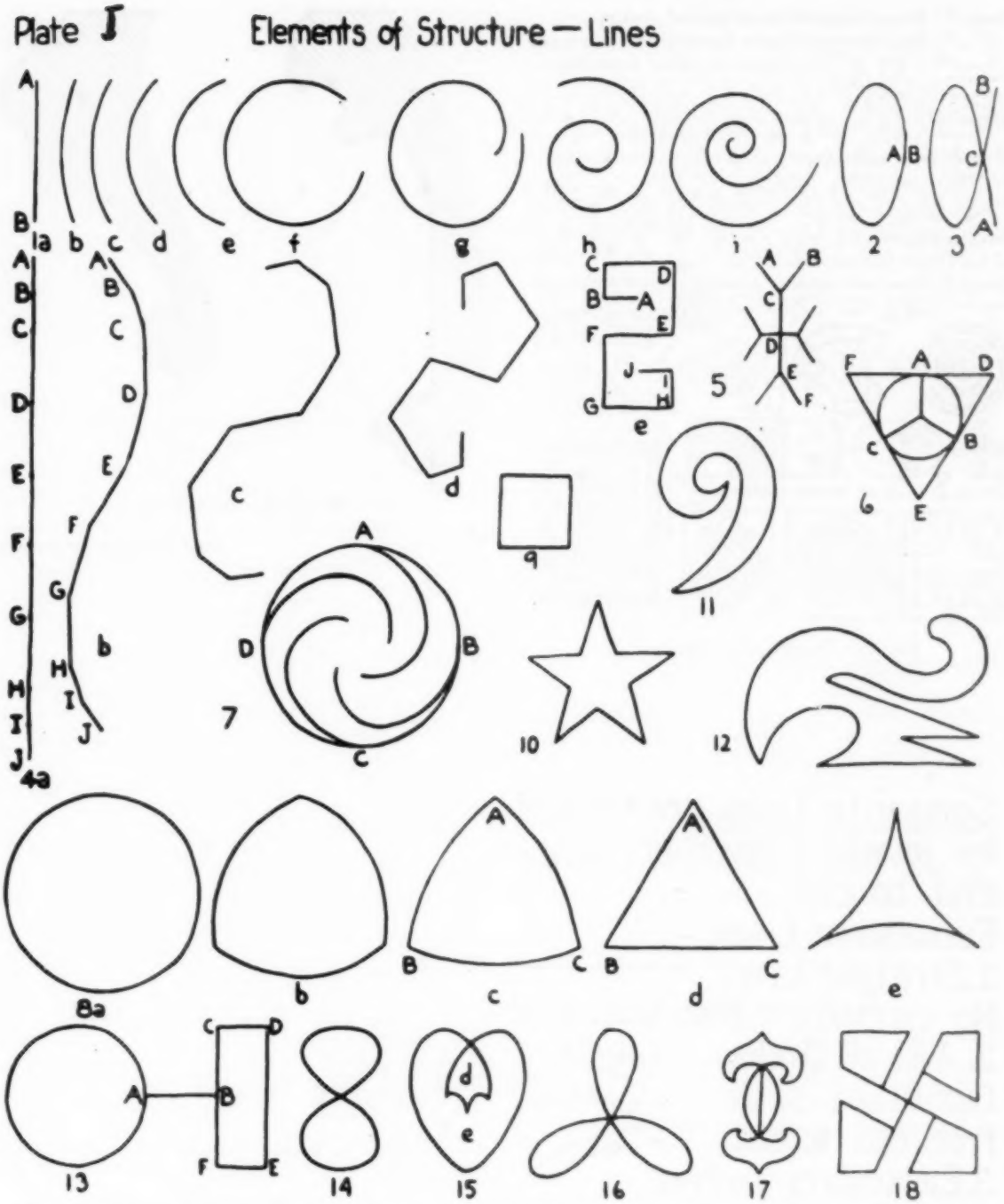

FIG. 14.—Elements of structure, lines; Nos. 1 (*a*) to 1 (*i*) and 4 (*a*) to 4 (*e*) are biterminals having two end points; Nos. 5, 6, and 7 are biterminals having one end point and biterminals connecting two junctions; Nos. 8 (*a*) to 8 (*e*) and 9 to 12 are aterminals; Nos. 13 to 18 are uniterminals.

8 (*e*) are aterminals. Number 8 (*d*) is a triangle, composed of three straight lines, which is true as to form; but structurally, it is a closed path from *A* to *B* to *C*, and back to *A* again. An aterminal must stand alone; its nature changes if any lines are attached to it. Other examples of aterminals are Nos. 9, 10, 11, and 12. The left side of No. 13 is a uniterminal, which starts at *A* and returns to *A* again; *BCDEFB*, on the right side, is also a uniterminal. Numbers 14 and 15 are each composed of two uniterminals, and No. 16 of three. A uniterminal must have some other line or lines joined to it. Structurally speaking, there are

Group A - No multi-adjacent nor self-adjacent domains
Figs 1,2-Aterminals, Figs 3,4-Bundles of three biterminals
Figs 5 to 9-Polyhedral Subdivisions
Group B-Some multi-adjacent but no self-adjacent domains
Bundles of four (Fig 10) &
of five (Fig 11) biterminals
Group C-Some self-adjacent domains
Figs 15-20 rank zero
Group D-Two or more subdivisions

FIG. 15.—Ovoidal lines, figures.

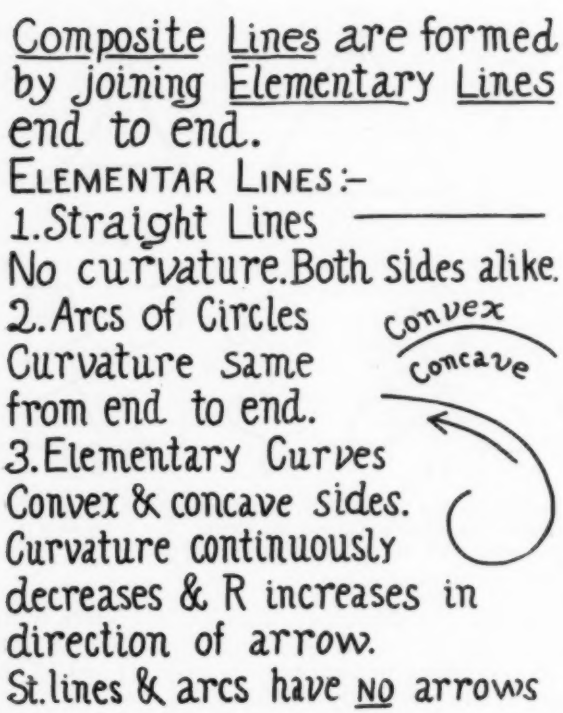

FIG. 16.—Types of elementary lines.

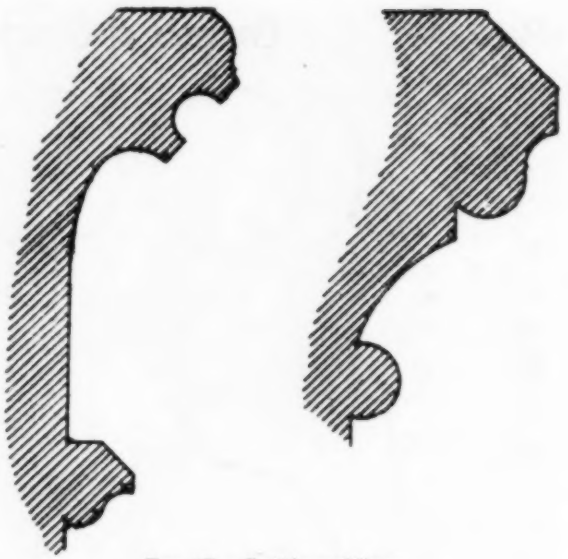

FIG. 17.—Gothic moldings.

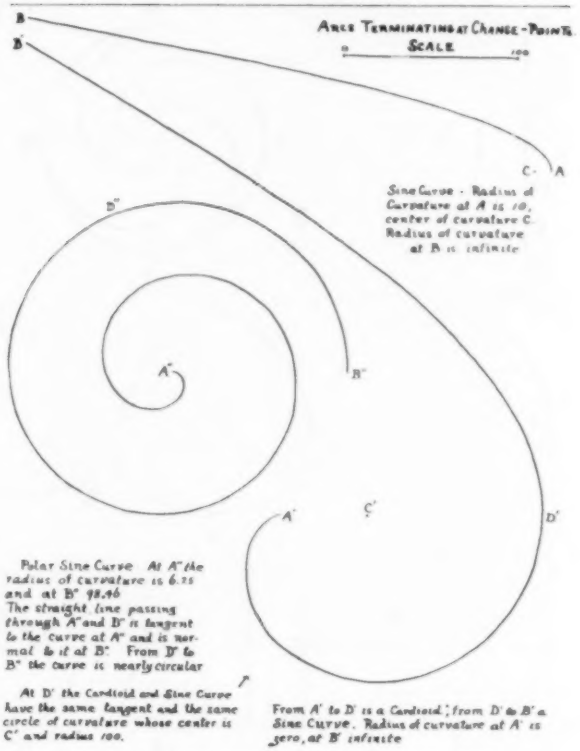
ARCS TERMINATING AT CHANGE-POINTS
SCALE
Sine Curve - Radius of
Curvature at A is 10,
center of curvature C.
Radius of curvature
at B is infinite
Polar Sine Curve At A" the
radius of curvature is 6.25
and at B" 98.96
The straight line passing
through A" and D" is tangent
to the curve at A" and is nor-
mal to it at B". From D" to
B" the curve is nearly circular
At D' the Cardioid and Sine Curve
have the same tangent and the same
circle of curvature whose center is
C' and radius 100.
From A' to D' is a Cardioid; from D' to B' a
Sine Curve. Radius of curvature at A' is
zero, at B' infinite

FIG. 18.—Arcs terminating at change points.

two kinds of points, (1) end points, exemplified by points *A*, *B*, and *F* in No. 5, and (2) junctions where lines meet, exemplified by *C*, *D*, and *E*, by *A* and *B* in No. 13, and by the middle of No. 16.

The areas bounded by lines of a figure are called domains. Figures that can be drawn on an ovoid, and on a sheet of paper, can be classified into four great groups designated by the letters *A*, *B*, *C*, and *D* (see Fig. 15). Group *A* includes the aterminal, (1) and (2);

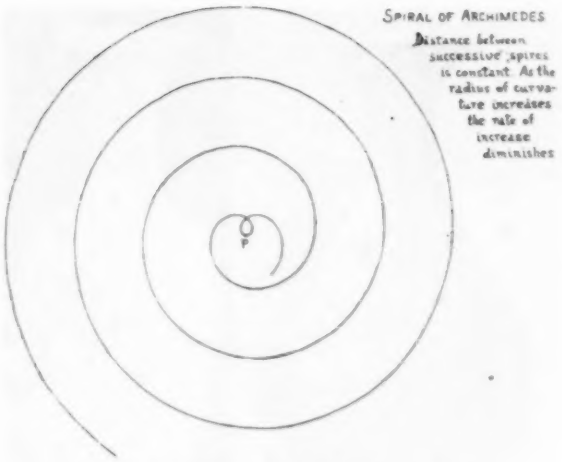
SPIRAL OF ARCHIMEDES
Distance between successive spires is constant. As the radius of curvature increases the rate of increase diminishes
P

FIG. 19.—Spiral of Archimedes.

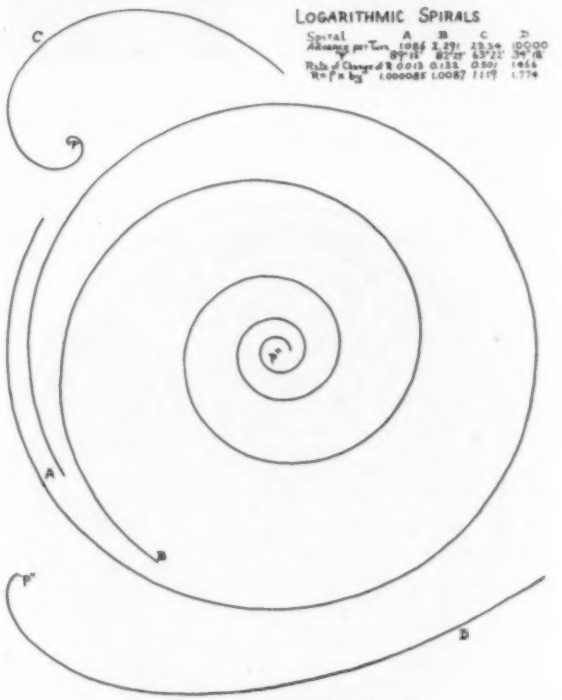

FIG. 20.—Logarithmic spirals.

FIG. 21.—Angles and cusps formed where segments meet.

the bundle of three biterminals, (3) and (4), and an endless array of polyhedral figures exemplified by (5) to (9), inclusive. The latter are composed of biterminals that lie between two different domains, and if two domains are adjacent along a line, as *b* and *c* in (7), or at a junction, as *b* and *d*, those two domains are not adjacent again. The figures of group *B* are composed of biterminals that lie between two different domains, but there are some pairs of domains that are adjacent more than once. The inner domain, *b*, and the outer domain, *d*, in (12) are adjacent at four junctions, and domains *b* and *d* in (13) are adjacent along two biterminals. The figures of group *C* have one or more self-adjacent domains. The domain surrounding (16) is self-adjacent at junction *A*, and the domain surrounding (21) lies on both sides of its five biterminals. The presence of a uniterminal results in self-adjacency, and this is the first time they have appeared. The figures of group *D* are composed of two or more disconnected parts. The dotted line is the frame or boundary of each figure; (26) and (27) are each composed of five aterminals but they are differently arranged with respect to one another.

It is interesting to note that any design that can be drawn on an ovoid can also be drawn on an annuloid, triannuloid, or higher fundamental surface. Any designs that can be drawn on an annuloid can also be drawn on a triannuloid and on any higher fundamental surface; but among designs that can be drawn on an annuloid are some that cannot be drawn on an ovoid. In the same way, there are figures that can be drawn on a triannuloid and on any higher fundamental surface that cannot be drawn on an annuloid or on an ovoid. Designers thus far have employed only ovoidal designs, those that can be drawn on an ovoid, although there is a close connection between designs that can be drawn on an annuloid and doubly repeating patterns, such as the checkerboard, the square and octagon used in tile floors, and many linoleum, carpet, and dress-goods patterns.

The author has not yet studied in detail the many classes of structures that are the subject matter of laminate graphics (section II). There are a few patterns of great antiquity, such as the two-strand rope and braids of three or more cords. Celtic art furnishes

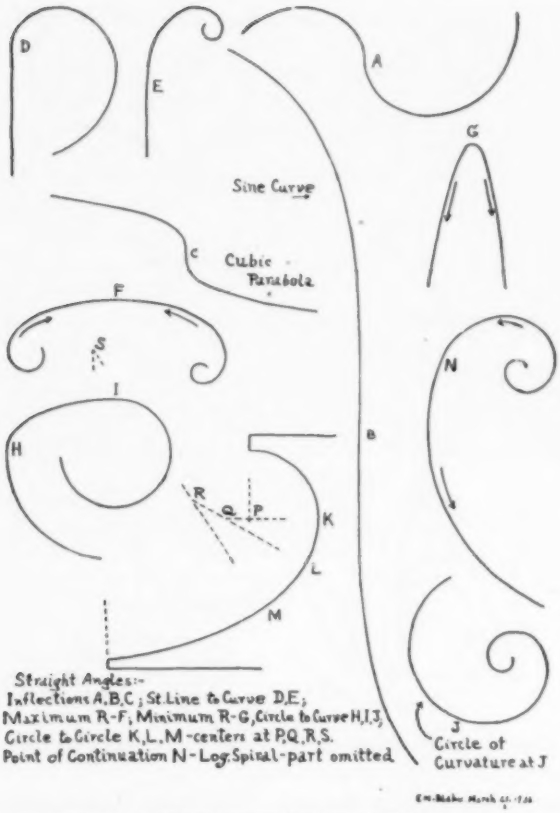

FIG. 22.—Inflections and other straight angles.

a wealth of suggestive patterns, a great many of which were collected, studied, and published by J. Romilly Allen. Mohammedan art likewise has much to give. Finally, about 1875 to 1890, P. G. Tait of Edinburgh and others made detailed studies of knots in an endless cord, and published plates of several hundred of the simplest. Figures 3 and 13 (*bottom*) are each based on one of those knots.

V. Fitting Design to Object to Be Decorated

In this method of design, all ovoidal designs are, in theory, drawn first on an ovoid, at least insofar as their structural characteristics are concerned; that is to say, the kinds and numbers of lines and the ways in which they are connected together. In practice, the work is usually done on a piece of paper. To pass from the ovoid to the piece of paper, a very small hole, called an eyelet, is cut in the ovoid, which can be given the form of a sphere and hollow. The surface is now stretched in such a way as to make the eyelet very large, and a bowl of thin material is the result. Further stretching and flattening will yield a flat disk that finally may be stretched into a rectangle, which is a piece of paper, the back of a playing card, or the face of a tile. While this stretching, bending, and shrinking has been going on, the lines that were drawn on the spherical ovoid have been changed in form, but their kinds, numbers, and connections have remained unchanged. The next step is to try to change the several lines into acceptable forms to make a creditable design. Colors are finally assigned to the several domains.

FIG. 23.—*Left*, Chinese porcelain vase, Metropolitan Museum of Art; *right*, Claire de lune, porcelain vase, Metropolitan Museum of Art.

FIG. 24.—Plate design.

Certain questions will doubtless occur. Whence come these structures that are drawn on the ovoid? The author hopes ultimately to supply a large collection, classified according to their salient structural characteristics, with methods for constructing countless other ones. Figure 15 shows the beginning of such a classification. Are not different figures obtained on the piece of paper or tile, depending on the location of

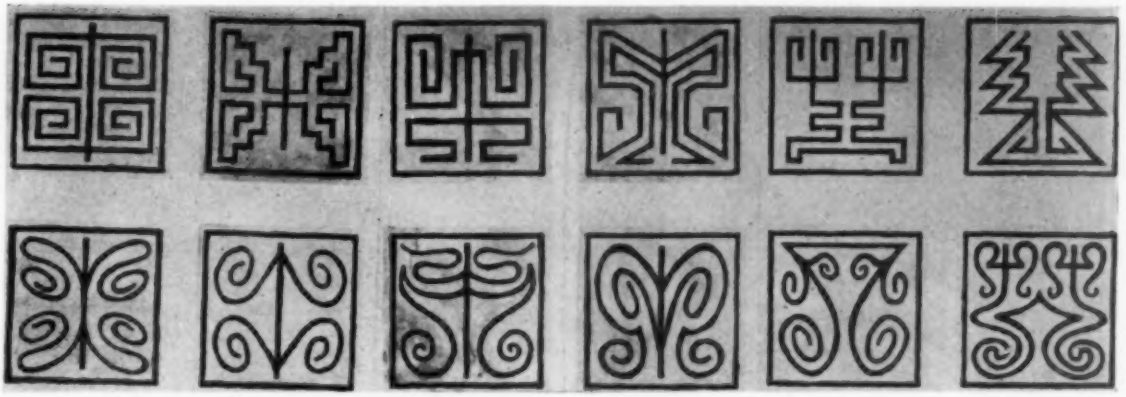

FIG. 25.—Tile designs.

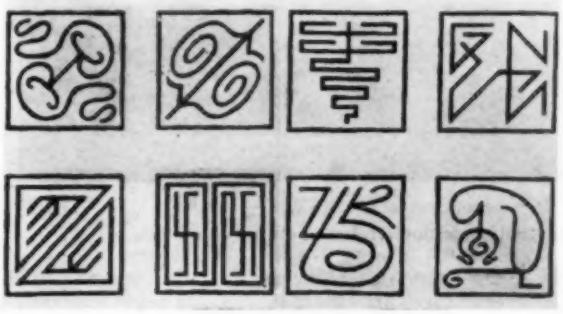

FIG. 26.—Tile designs.

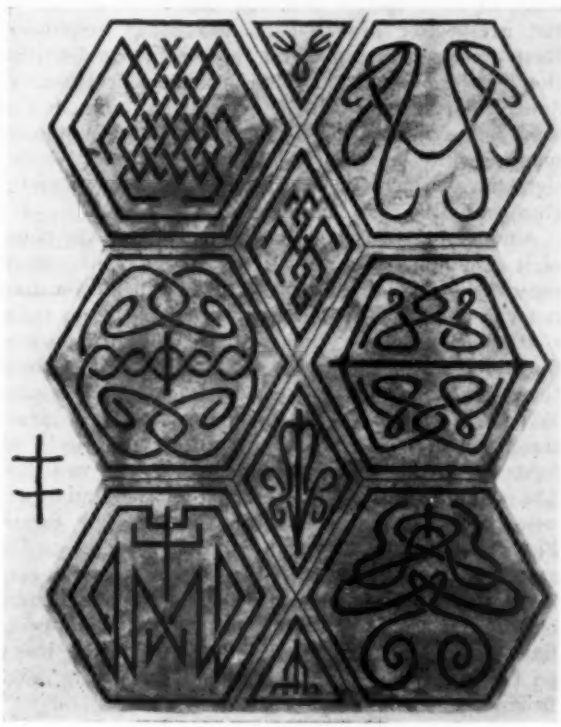

FIG. 27.—Tile designs.

the eyelet? This is true usually, at least two or three dozen different figures may be obtained. How to obtain form will be described later.

If a vase without handles is to be decorated, two eyelets are cut in the ovoid, one for the opening of the vase and the other for the base. The decoration should extend neither down into the vase nor under the bottom. To fit a vase with four openings, five eyelets must be cut in the ovoid.

VI. Graphic Form

Drawing on a plane will alone be considered, but if plane graphic form is understood, drawing on a curved surface can readily be mastered. Three kinds of elementary lines are available (Fig. 16). A line of a design may be (1) straight, (2) an arc of a circle, or (3) an arc whose curvature continuously decreases from one end to the other. There is still another possibility, suggested by the profiles of the Gothic moldings, Fig. 17, which is to divide a line into two or more segments and to make each segment a straight line, an arc of a circle, or an elementary curve, these joined end to end, meeting one another at cusps, angles, or inflections. Elementary arcs are of several varieties. Figure 18 shows the sine and polar sine curves; Fig. 19, the spiral of Archimedes; Fig. 20, the celebrated logarithmic spiral, which furnishes a variety of forms. Of course, a whole spiral cannot be used because it goes to infinity, but a portion may be selected according to the purpose of its use.

Anyone who understands coordinate geometry can draw these curves and others from their equations with great accuracy and of any size. For classroom instruction, they can be made as wall charts and serve much as the model does in the life class. The student would copy them free hand and thus train hand, eye, and mind to appreciate the beauties of continuously varying curvature. Having had this training, the designer would draw his curves free hand, except in rare cases.

Figure 21 shows angles and cusps formed where one segment meets another, and Fig. 22 shows inflections and other straight angles.

The study of plane form is also of service in designing the contours of vases to be turned on the potter's wheel, as illustrated by the two Chinese examples shown in Fig. 23.

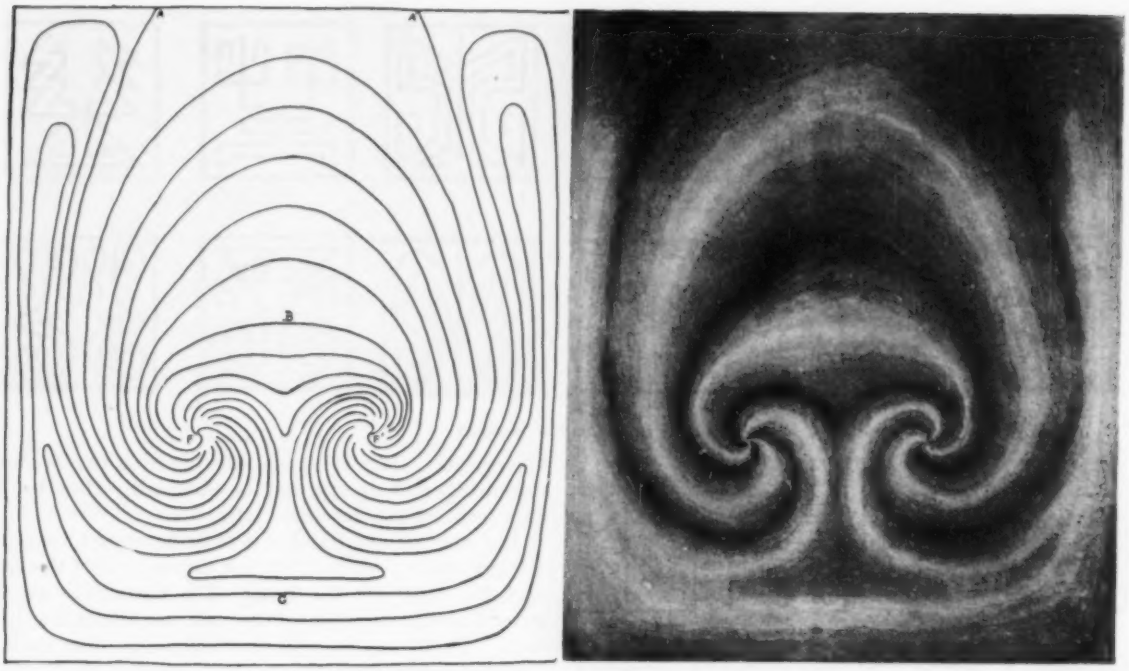

FIG. 28.—*Left*, system of isotonics; *right*, singly varitonic domain based on isotonic lines.

VII. Examples of Method

The plate design, Fig. 24, was an answer to the problem, namely, to make a plate design repeating five times about its center, the repeat being two isolated biterminals. The structure of the repeat (not its form) is given, the problem being to make the repeat into a pleasing form. How many other answers to the problem might not be made? The mere fact of being confined to a specific structure but free as to the form into which it may be thrown is stimulative of creative effort.

The author, in 1921, made some simple tile designs to test the method. Those that are shown are based on a simple graphic figure consisting of a central biterminal to each end of which three biterminals are attached, see left margin, Fig. 27. The first four tile at the left in Fig. 25 have two axes of symmetry and have a two-fold cyclic repeat about their centers; the four middle designs in Fig. 25 are structurally the same as those at the left but they have only an axis of symmetry running along the central biterminal; the four tile at the right (Fig. 25) have only an axis of symmetry crossing the central biterminal. The four tile at the left in Fig. 26 have no symmetry, but unlike those in the middle and right groups of Fig. 25, they have a two-fold cyclical repeat about their centers. Finally, the four tile at the right in Fig. 26 have neither symmetry nor cyclical repeat. The tile of Fig. 27 bear laminate designs, structurally the same as those of Figs. 25 and 26 but having their biterminals crossing one another. The underlying structure is shown at the left in Fig. 27.

VIII. Coloring of Domains

The selection of colors and color combinations belongs to the esthetics of design, not to its geometry, but irrespective of the particular colors employed, there are certain methods for the continuous distribution of color over domains that merit consideration. A domain is isotonic when the color at any point is the same as the color at every other point. Thus a domain may be white or red or green. Many decorative designs have their domains isotonically colored, thereby cheapening the cost of production.

A domain is singly varitonic when through any point of it, excluding one or two exceptional points, there passes a line, called an isotonic, along which color does not change, but in passing across the isotonics color continuously changes. The isotonics that lie across any domain constitute a system of isotonics, and of these there are about fifteen structurally different kinds. Figure 28, *left*, shows one system of isotonics, characterized by having all isotonics run from focus F to focus F'. All colors employed meet at the two foci. The isotonics must not intersect one another, but otherwise there is great latitude in selecting their forms. Figure 28, *right*, is a domain painted according to the system of isotonics shown at the left, the colors ranging from yellow to green. Figure 29, *left*, is a second system of isotonics which has no foci, the points F and F' being finial points; at the right (Fig. 29) is a painting based on the isotonics shown at the left. The colors range from red at F to blue-green at F'.

There is a third type of continuous color distribution called doubly varitonic. Such a domain may have

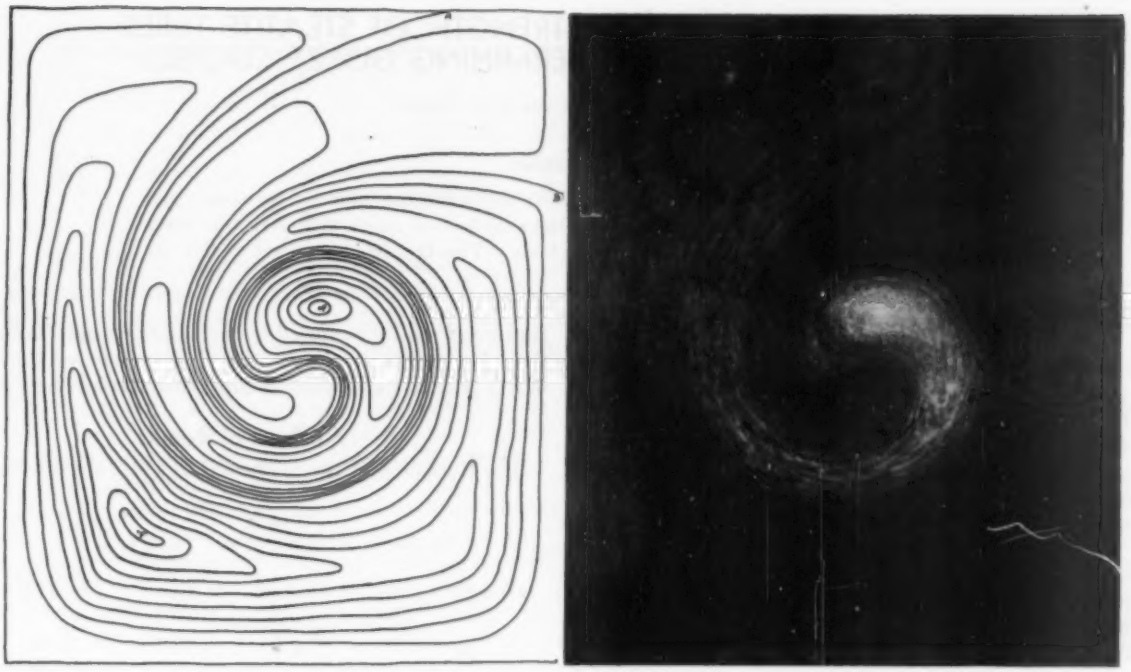

FIG. 29.—*Left*, system of isotonics; *right*, singly varitonic domain based on isotonic lines.

one line on it along which color does not change, but from any point P not on that line color will be different from that at P at all points near P. These domains are difficult of execution on account of the large number of colors that must be mixed to achieve reasonable continuity of color tone.

IX. Geometric Structure

Structure is a comparatively new idea in geometry dating only from 1847, but it has thrown a broad light on geometrical study during the past half century. In classifying the figures of value to design, taking account of their structural characteristics only, discrete objects are used. A figure contains ten lines or eleven lines as the case may be, but never ten and thirteen-sixteenths of a line. Forms are much more numerous and they differ from one another by imperceptible gradations. In Fig. 14, Nos. 8 (*a*) to 8 (*e*), 9, 10, 11, and 12 are structurally identical, all being aterminals. How many hundreds of other forms might not be made? There is an infinity of regular triangular forms between Nos. 8 (*b*) and 8 (*e*). Anyone making a classification of figures according to their forms would soon find it necessary to take cognizance of underlying structure. A good classification will show the designer the very great number of varieties of structures available and place them within his reach.

Geometric designs, based as they usually are on form, are frequently simple, crude, inflexible, although they may be of any degree of complexity, highly organized, refined, and graceful. The procedure here advocated to create a design is, first, to select a structure, that would seem suited to the work in hand, from among the great number of varieties that a detailed classification discloses. An entirely definite thing is obtained with respect to the kinds and numbers of its lines and their connections, a thing, nevertheless, that is capable of great fluidity of form, comparable with the aggregate of postures the human figure is capable of assuming. The second step is what may be termed "an adventure in form," the endeavor to make the form of the structure satisfactory. The designer is bound to definite kinds and numbers of lines and their connections at junctions, but he is free as to form and he may concentrate his attention on the problem, bringing to bear his knowledge of line forms, curvatures, proportions and spacing, a condition that is stimulative of successful creative effort.

Not only may the structural approach be employed in the creation of designs, but designs may be classified and appreciated for their underlying structures, and anyone who has acquired the structural point of view will look below the form to the foundation on which it rests.

MOUNT KISCO, NEW YORK

INFLUENCE OF GLAZE ON STRENGTH OF STEATITE TUBES AND NEW METHOD OF DETERMINING GLAZE STRESSES*

By J. J. Gingold and E. J. Hirsh

Abstract

Different glazes have been applied on steatite tubes and the influence on impact and flexural strength has been investigated. Glazes applied on tubes with very thin walls affect the thermal expansion of the ceramic body. This fact has been used to test the glaze fit.

I. Introduction

It is known that the strength of ceramic materials can be increased by an appropriate glaze if, and when, the thermal expansion of the glaze is lower than that of the body, in which case the glaze is submitted to compression. This effect is easily realized in steatite as it has a relatively high thermal expansion in comparison to most of the high-fired glazes.

Most of the experiments known and published so far deal with solid bars and insulators. In the course of development work on steatite tubes, the writers have made observations which show that the glaze does not always increase the strength.

A number of tubes were extruded from two different steatite bodies. Their fired dimensions were, approximately, outside diameter 0.7 in. and inside diameter 0.15 in. The tubes were fired hanging and after firing they were cut to a length of 6 in. One part was fired unglazed, another glazed outside, a third inside, and a fourth inside and outside. One series was glazed before the first fire; another before the second fire. Four different glazes were applied. The glazes 3R and 3F are chemically identical; glaze 3R is a raw glaze and 3F is the same glaze fritted.

Impact strength and modulus of rupture were tested. A Charpy pendulum hammer was used for the impact strength test which was computed from formula (1).

$$\text{Impact strength (ft.-lb./sq. in.)} = \frac{\text{pendulum energy expended in breaking}}{\text{section}} \qquad (1)$$

Formula (2) was used to compute the modulus of rupture.

$$\text{Modulus of rupture (ft.-lb./sq. in.)} = \frac{5.1 \times P \times \text{O.D.}}{\text{O.D.}^4 - \text{I.D.}^4} \qquad (2)$$

P = breaking load.
O.D. and I.D. = outside and inside diam.
Factor 5.1 includes edge distance of 2 in.

The inside diameter of the series which was glazed on the outside differed from the remaining samples. According to investigations carried out by one of the writers,[1] the impact strength as well as the modulus of rupture of the tubes varied with changing inside diameter. The results shown in Table I, therefore, establish only a general trend without supplying absolute figures.

II. Analysis of Results

The thickness of the applied glazes introduce a fac-

Table I

Glaze No.	Fire	Impact strength	Flexural breaking load	Modulus of rupture
Body No. 1: O.D. 0.69 in.; I.D. 0.44 in.				
		Unglazed		
	1	2.35	5.47	10,400
	2	"	"	10,900
		Outside glazed		
1	1	2.45	489	8,790
	2	1.64	588	10,200
2	1	2.16	476	7,780
	2	2.20	534	9,600
3R	1	2.06	479	8,900
	2	2.00	573	10,700
3F	1	1.93	490	8,800
	2	2.22	566	10,600
Body No. 1: O.D. 0.69 in.; I.D. 0.50 in.				
		Unglazed		
	1	2.16	352	7,550
	2	1.98	335	7,150
		Inside glazed		
1	1	1.87	532	10,100
	2	2.06	387	8,290
3R	1	1.76	546	10,200
	2	1.98	385	8,290
3F	1		530	10,100
	2	2.06		
		Glazed inside and outside		
1	1	1.72	466	8,010
	2	2.15	429	8,450
3R	1	1.75	430	7,860
	2	1.83	361	7,100
3F	1	1.78	563	9,800
	2	1.89	350	7,130
Body No. 2: O.D. 0.68 in.; I.D. 0.43 in.				
		Unglazed		
	1	2.42	640	12,560
	2	2.48	672	13,200
		Outside glazed		
1	1	2.50	558	10,050
	2	2.44	633	11,700
2	1	2.38	562	10,200
	2	2.94	611	11,500
3R	1	2.15	540	10,200
	2	2.80	639	12,430
3F	1	2.48	520	9,900
	2	2.90	660	12,820

* Forty-Seventh Annual Program, The American Ceramic Society, 1945 (White Wares Division, No. 3). Received March 11, 1945.

[1] J. J. Gingold, "Mechanical Abnormalities of Ceramic Materials," listed on Forty-Seventh Annual Program (to be published later).

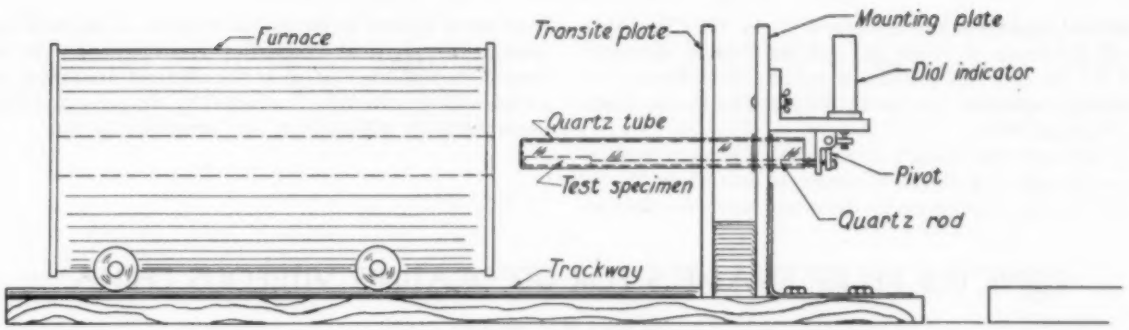

FIG. 1.—Homemade dilatometer for thermal-expansion test.

tor of uncertainty in the computed figures because of the different nature of body and glaze. The values of the flexural breaking load, therefore, are added to those of the computed modulus of rupture.

The tubes glazed on the outside have a lower modulus of rupture than those unglazed. The one-fire application shows a more marked decrease than the two-fire application. The inside glaze has the effect of increasing the flexural strength and this increase is higher for the one-fire specimens. The tubes glazed on the outside and inside show less increase in strength than those glazed only on the inside. The impact strength behaves irregularly and no definite trend could be found. In comparing the figures for the flexural breaking load, the picture does not change.

The well-known ring method was used for further investigation of the glaze-body stresses.[2] Rings were cut from extruded tubes with an outside diameter of $2^3/_4$ in., inside diameter $2^9/_{16}$ in., and length 1 in. The glaze was applied inside these rings.

The inside glaze being under compression tended to open the ring after firing when a longitudinal incision on the outside was made with a fine grinding wheel. No significant difference could be observed between the different glazes. The glaze-body stresses, however, were positively reduced in the case of the second fire glazing.

III. Results

In case of considerable glaze-body stresses (one-fire application) the outside glaze causes a marked decrease of the modulus of rupture. The inside glaze, on the contrary, showed a considerable amount of increase. In the case of the two-fire application, the glaze-body stresses are much less marked and the change of the modulus of rupture is much less.

When a glaze under compression is applied on the outside of ceramic tubes, it tends to contract them and produces a compression force directed to the center. It is obvious that this internal-compression stress acts in the same sense as any external force applied in radial direction. For this reason, the flexural breaking load will be decreased. On the other hand, a glaze under compression applied on the inside produces an internal force in radial direction tending to expand the tube. It will therefore act in the opposite sense of the applied external force, and the breaking load will be higher than for the unglazed cylinder.

The stresses set up in the body by glazing on the inside are very high. This was evidenced by the fact that, after firing, many of the test specimens split open by themselves after a certain time. These stresses were sufficient to change the shrinkage of bodies glazed in this manner. A considerable amount of difference was noticed in the outside diameter through the influence of the glaze as shown in Table II.

TABLE II

OUTSIDE DIAMETER OF TUBES OF BODY NO. 1

I.D., 0.5 in.

Fire	Unglazed	Glaze 1	Glaze 3R	Glaze 3F
1	0.689	0.697	0.698	0.705
2	0.690	0.688	0.688	0.698

TABLE III

RELATIVE THERMAL EXPANSION, 0.10^4, BODY NO. 1, ONE-FIRE

Temp. (°F.)	Unglazed	Glaze 1	Glaze 3R	Glaze 3F
85	0	0	0	0
100	0.65	0.29	0.38	0.24
200	4.01	3.61	3.34	3.39
300	7.64	6.62	6.41	6.94
400	12.03	10.27	10.00	9.98
500	16.05	14.1	13.4	13.65
600	20.2	18.05	17.1	17.57
700	24.2	21.4	20.6	20.9
800	28.5	25.6	24.4	24.72
900	33.7	30.4		29.95
1000	38.6		33.8	
1100	42.7	39.6	37.6	38.4
1200	47.3	43.6	41.5	42.5

The outside diameter is increased here by approximately 0.01 in. in the first-fire application where the very high stresses occur. In the second fire application, practically no change could be observed.

As has been shown, the influence of the glaze on mechanical and dimensional properties is important. To ascertain the effect of the glaze on the thermal expansion of a ceramic tube, tubes with different wall thicknesses, glazed inside and outside, were submitted to a thermal-expansion test in a homemade dilatometer. The latter is shown in Fig. 1.

The dial indicator measuring the expansion of a test specimen 3 in. long has a sensitivity of 0.0001 in. The

[2] W. C. Bell, "Study of Glaze Stresses," *Ohio State Univ. Eng. Expt. Sta. Bull.*, No. 114, 28 pp. (May, 1943); *Ceram. Abs.*, **22** [9] 156 (1943).

thermal expansion was measured up to 1200°F. At a wall thickness of 0.048 in. and an outside diameter of 0.5 in. (see Table III), a noticeable difference of thermal expansion was finally obtained for the unglazed and glazed tubes.

Although the writers have been able to reproduce measurements with an accuracy of less than 1% at 1200°F., they prefer not to draw any hasty conclusions from these figures as far as the relation of thermal expansion to physical properties is concerned. It is clearly shown, however, that the thermal expansion of a thin-wall steatite tube is affected by the glaze and this most probably will apply to any ceramic material.

General Ceramics and Steatite Corporation
Keasbey, New Jersey

CONE 015 RELIEF ENAMELS FOR DECORATING VITREOUS CHINA*

By John H. Voorhies

Abstract

Relief enamels must remain in relief and not flow down during maturing fire. They must also have adequate acid and abrasion resistance; they should not craze and they should accommodate as wide a color range as possible. The relief enamel developed in this study satisfies these various qualifications.

I. Introduction

Overglaze colors and enamels heretofore have been fired several cones higher than the gold decorations. Overglaze colors for the most part could be fluxed to make them usable at cone 015, but to flux the relief enamels to fire at this cone would damage some of the qualities essential to good relief enamels. It seemed advisable, therefore, to develop a relief enamel base for cone 015 that would more adequately meet the need.

Three conditions and limitations are involved in producing relief enamels as follows: (1) they must have adequate acid and abrasion resistance; (2) their coefficient of expansion must be such that there will be no crazing when they are applied to the china glaze; and (3) they must also accommodate a wide range of colors in order to maintain various color schemes and patterns.

II. Historical Survey

Binns[1] gives several recipes for enamel colors and fluxes, but these are mainly lead borosilicates and as such do not possess sufficient acid and abrasion resistance to qualify. Eisenlohr,[2] in 1929, developed vitreous colors with the introduction of lithium, as follows:

PbO	0.9		
K_2O	0.05	SiO_2	1.50
Li_2O	0.05		

In 1940, Watts[3] found that to stabilize such low firing colors, it was necessary to increase the silica content and to add alumina to the composition. This procedure obviously raised the firing temperature and viscosity of the overglaze colors. The fact that overglaze colors are not so fluid would be an advantage as far as relief enamels are concerned.

III. Procedure

The investigation outlined was (1) to increase the RO group by adding BaO, BeO, CaO, MgO, SrO, and ZnO, (2) to raise the Li_2O content, (3) to introduce a small amount of fluorine, and (4) to provide an opacifier in place of tin oxide.

Several series of samples were made up, using as two members of triaxial diagram the bases developed by Watts and Eisenlohr. The third members of the triaxial series were, respectively, Babosil, lepidolite, strontium carbonate, and a frit (10% beryl to Eisenlohr's base). The frit batches were weighed, screened together several times, and fired in crucibles to cone 03. They were then wet ground for 15 hours and run through Ferro filter and dried.

The several members of these series were weighed and ground together with water (10% mucilage addition) in a small porcelain mortar until smooth enough to paint with a brush. They were then applied to china glaze in several thicknesses and fired to cone 015 on an 18-hour cycle.

When the results of the first four series had been checked and recorded, further series were tried. These experiments were extended over a considerable period of time and were distinctly progressive in nature. When favorable results were obtained, changes were made, and further trials were run.

Inasmuch as this is a new field of investigation, the writer wanted to obtain as wide a coverage as possible. Much time and effort were given to trials that were absolute failures, but these negative results also yielded valuable information.

IV. Results

Member No. 6, series 14, selected as the most suitable relief enamel, had the following percentage composition:

* Forty-Seventh Annual Program, The American Ceramic Society, 1945 (Design Division, No. 6). Received February 26, 1945.

[1] C. F. Binns, Manual of Practical Potting. Scott, Greewood, & Son, London.

[2] H. Eisenlohr, "Method for Manufacture of Acid-Resistant Fluxes for Enamel," U. S. Pat. 1,927,737, Sept. 19, 1933.

[3] A. S. Watts, "Decalcomania: Proposed Development," *Jour. Amer. Ceram. Soc.*, **23** [11] 341–42 (1940).

PbO	57.600	Al_2O_3	2.898
K_2O	0.630	SiO_2	31.720
Li_2O	0.245	ZrO_2	6.580
BeO	0.198		
		Total	99.871

It also had an empirical composition as follows:

PbO	0.9200			SiO_2	1.88
K_2O	0.0238	0.101	Al_2O_3	ZrO	0.191
Li_2O	0.0288				
BeO	0.0281				
	1.0007				

The same member (No. 6, Series 14) was made from a 50% blend of two frits, (*A*) and (*B*) as follows:

	(*A*) Frit	(*B*) Frit
PbO	64.101	51.20
K_2O	0.70	0.56
Li_2O	0.27	0.23
BeO	0.22	0.17
Al_2O_3	3.22	2.57
SiO_2	31.50	32.00
ZrO_2		13.10
	99.91	99.83

The lithium was introduced from lepidolite, and the zirconia from Zircopax. Their chemical composition follows.

Lepidolite	(%)		(%)	Zircopax	(%)
K_2O	10.33	Al_2O_3	26.77	ZrO_2	65.82
Na_2O	0.13	SiO_2	52.89	SiO_2	33.56
MgO	0.31	MnO_2	0.59		
Li_2O	4.65	F_2	3.68		99.38
Fe_2O_3	0.19	Ignition loss	0.66		
		Total	100.20		

This enamel gave satisfactory results when it was applied over a vitreous china dinnerware glaze. At cone 015, it had a good glossy finish, it did not craze, it stood up well in relief, and it permitted a wide range of colors. Care should be taken not to grind this enamel too fine because excessive grinding causes crawling. Fifteen hours of wet grinding were sufficient to obtain good results.

V. Conclusions

These trials indicate that it is possible to produce a satisfactory relief enamel at cone 015 and, in general, the results lie between those obtained by Watts and Eisenlohr. The RO group, however, has been increased by the addition of BeO and the RO_2 group by ZrO_2. It is quite possible that further investigation could improve the results thus far obtained.

GLADDING, MCBEAN & COMPANY
LOS ANGELES 26, CALIFORNIA

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